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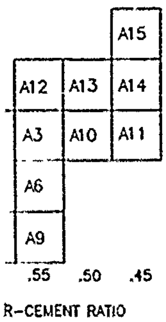

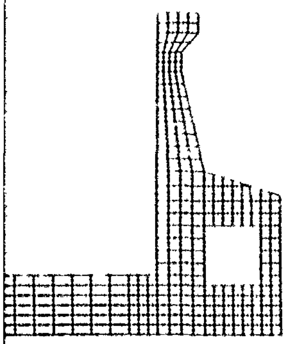

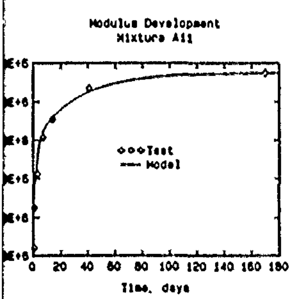

STRUCTURES LABORATORY

TECHNICAL REPORT SL-90-8

RED RIVER WATERWAY THERMAL STUDIES

Report 1

CONCRETE MIXTURE SELECTION AND CHARACTERIZATION

by

Michael I. Hammons, Donald M. Smith, Billy D. Neeley

Structures Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

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for report
This is the first of two reports documenting the findings of the Red River Waterway Thermal Study. It includes the selection and characterization of the concrete materials in support of thermal- and incremental-construction analyses. The primary objective was to develop and evaluate materials and construction methods which would yield safe, serviceable structures with lower life-cycle costs. Materials (Type II portland cement, Class C fly ash, and aggregates) were selected based upon materials likely to be used in the construction of Locks and Dams 4 and 5. These materials were characterized and used to develop 15 trial concrete mixtures. Ratios of Class C fly ash to total cementitious materials from 0.25 to 0.60 were studied. Water-cement ratios were varied from 0.45 to 0.65. These mixtures were evaluated based upon strength requirements, economy, and thermal considerations. From the 15 mixtures, 4 candidate mixtures were selected for complete thermal and mechanical properties characterization. Tests included thermal properties, adiabatic temperature rise, creep, elastic modulus, shrinkage, and compressive strength. Keywords;

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PREFACE

The investigation described in this report was conducted for the US Army Engineer District, Vicksburg. Authorization was given by DA Form 2544, No. 4908, dated 30 Dec 1987, and subsequent revisions. Funds for publication of this report were provided by the Concrete Technology Information Analysis Center (CTIAC). This is CTIAC Report No. 87.

The investigation was performed at the US Army Engineer Waterways Experiment Station (WES) by members of the staff of the Structures Laboratory (SL), under the general supervision of Messrs. Bryant Mather, Chief, SL, and J. T. Ballard, Assistant Chief, SL. Direct supervision was provided by Mr. K. L. Saucier, Chief, Concrete Technology Division (CTD). Project Management was provided by Mr. Michael I. Hammons, Group Leader, Applied Mechanics Group (AMG), Engineering Mechanics Branch (EMB), CTD. This report was prepared by Mr. Hammons and Mr. Donald M. Smith, AMG, and Mr. Billy D. Neeley, Applications Group, EMB. The authors acknowledge Dr. C. Dean Norman, Structural Mechanics Division, SL, Ms. Sharon B. Garner, Mr. Anthony Bombich, Mr. Dan Wilson, Mr. Brent Lamb, Ms. Linda Mayfield, and Mr. James Shirley, AMG, for their help during this investigation. The authors also acknowledge the assistance of Messrs. Toy Poole, Sam Wong, Michael Lloyd, Percy Collins, Tom Lee, Julies Mason, and Ken Loyd, CTD, and MAJ Stacey Hirata of the US Military Academy. In addition, the authors acknowledge the technical direction of the Red River Thermal Study Advisory Panel members, Mr. Mather, Mr. Fred Anderson, Headquarters, US Army Corps of Engineers, and Prof. W. L. Dolch, Purdue University.

Commander and Director of WES is COL Larry B. Fulton, EN. Technical Director is Dr. Robert W. Whalin.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
Btu (International Table) per pound (mass) · degree Fahrenheit	4,186.8	joules per kilogram kelvin
Btu (International Table) feet per day · square foot · degree Fahrenheit	5,981.41947	watts per metre kelvin
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
feet	0.3048	metres
inches	25.4	millimetres
miles	1.609	kilometres
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C + (5/9)(F - 32). To obtain kelvin (K) readings, use K = (5/9)(F - 32) + 273.15.

RED RIVER WATERWAY THERMAL STUDIES

CONCRETE MIXTURE SELECTION AND CHARACTERIZATION

PART I: INTRODUCTION

Background

1. In 1968 Congress enacted Public Law 90-483 which authorized the construction of the Red River Waterway in Louisiana, Arkansas, Texas, and Oklahoma. As a part of this act, Congress directed that the Red River be made navigable from its juncture with the Mississippi River to Shreveport, Louisiana. This improvement includes developing a 9-ft deep, 200-ft wide navigation channel along approximately 236 miles of river.* A system of five locks and dams is required along the channel to furnish a maximum lift of 141 feet. Locks and Dams 1 and 2 were completed in 1984 and 1987, respectively. In 1989 Lock and Dam 3 was under construction, and construction of Locks and Dams 4 and 5 was scheduled to begin in 1992.

2. Both Locks and Dams 1 and 2 experienced significant cracking with Lock and Dam 1 requiring remedial grouting. This cracking is believed to have resulted from stresses induced as the concrete cooled under restraint. Also, similar cracking has been observed on locks and dams constructed by the Vicksburg District on the Ouachita and Black Rivers in Louisiana and Arkansas. Although this cracking usually does not pose a threat to structural integrity, it leads to increased maintenance costs and possible shortening of service life. The Vicksburg District and Lower Mississippi Valley Division recognized the need for a careful and deliberate thermal stress analysis to be conducted on Locks and Dams 4 and 5. Consequently, the Concrete Technology Division (CTD) of Structures Laboratory (SL), USAE Waterways Experiment Station (WES) initiated the Red River Waterway Thermal Studies in January 1988.

3. The thermal and incremental construction analysis procedures used for the study were developed at WES beginning in 1984 to provide a modern,

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page iv.

consistent, and effective method of analysis to predict cracking in mass concrete structures. This analysis procedure allows better definition of concrete material properties and construction procedures which lead to safe, serviceable, and cost-effective mass concrete structures. The analysis tool is a two- or three-dimensional finite-element model for concrete which includes change in material properties with time, creep, shrinkage, and thermal effects. Through the use of this model in a proven general purpose heat transfer and structural analysis code, different concrete mixtures can be accurately simulated in the construction analysis of a structure or critical structural component. From this analysis the engineer can determine the concrete mixture and construction procedures which will yield the most cost-effective and serviceable structure for the given field conditions and practical construction constraints.

4. This report is the first of two documenting the findings of the Red River Waterway Thermal Study. It includes the selection and characterization of the concrete materials in support of the thermal and incremental-construction analysis. The second report will include the results of the thermal stress analyses and specific recommendations to limit thermal-related cracking in Locks and Dams 4 and 5.

Objective

5. The primary objective of this research program was to develop and evaluate materials and construction methods which would yield safe, serviceable, long-lived, and cost-effective structures. All products of the research were carefully scrutinized to determine if they were practical for field application. The results of laboratory tests were used to make specific recommendations intended to limit production of heat during the hydration process and reduce costs by using increased levels of replacement of portland cement with fly ash. Also, the results of the finite-element analyses were used to recommend improved construction practices intended to limit thermal stresses and related cracking.

Scope

6. This research effect can be divided into two integrated phases: concrete materials selection and characterization and thermal and incremental-construction analyses. Each of these phases is discussed below.

7. Prior research and field experience have proven that the critical material property parameters affecting cracking in mass concrete are time-dependency, creep, shrinkage, heat production, and thermal properties. A preliminary mixture proportioning study was conducted to investigate the appropriateness of using increased levels of fly ash as a cementitious material to limit heat production during early hydration and reduce the total cost of cementitious materials. The results of this study were used to select a few representative candidate mixtures for a full suite of mechanical and thermal properties tests. These tests were designed to determine the values of critical material response parameters at early ages when time- and temperature-dependent changes in these parameters are occurring most rapidly and thermal-related cracking is most likely to occur.

8. Crack surveys of Lock and Dam 2, Red River Waterway, were studied prior to selecting critical structural features for analysis. These features were discretized to allow incremental construction finite-element analysis. The material and thermal properties test data were used to calibrate state-of-the-art thermal and mechanical material models. The previously defined critical sections were analyzed using two- and three-dimensional finite-element models. Variations in placement and ambient temperature, concrete mixtures and temperature control parameters were analyzed for control of thermal stresses.

PART II: MATERIALS CHARACTERIZATION

General

9. In support of the thermal stress analyses, materials typical of those likely to be used to construct the locks and dams were chosen for laboratory testing. These materials were recommended to WES by the Foundation and Materials Branch, Engineering Division, Vicksburg District, based upon an extensive study of suitable sources of cements, pozzolans, and aggregates. Samples of the materials were obtained by WES in sufficient quantities to conduct characterization tests and prepare trial mixtures for the mixture proportioning study described in Part III of this report. In this chapter the aggregates and cementitious materials are described and the results of characterization tests are reported.

Aggregates

10. Based upon the recommendations made by Vicksburg District of aggregate sources typical of those likely to be used on the project, the following aggregates were obtained from the listed sources:

a. Fine Aggregate: Cobb Industrial Corporation, Coushatta, Louisiana

b. 4.75-mm to 19.0-mm (No. 4 to 3/4-in.) Aggregate: Western Gravel Co., Inc., Jena, Louisiana

c. 19.0-mm to 37.5-mm (3/4-in. to 1-1/2-in.) Aggregate: Granite Mountain Quarries, Sweet Home, Arkansas

A brief description of each of these aggregates follows.

11. The 3/4-in. and smaller aggregate chosen for this investigation is typical of those normally used in the Lower Red River Valley region. It is a natural sand composed of blocky, ellipsoidal, and spherical particles. Chert is the primary constituent in sizes larger than 2.36 mm (No. 8) with quartz predominating in the smaller sizes. The #4 to 3/4-in. aggregate is a primarily pale yellowish brown chert composed of blocky, pyramidal, and tabular particles with rounded edges and corners. Quartz and other miscellaneous particles make up the remainder of the constituents. Grading

and other physical characteristics of the aggregates are given in Appendix I.

12. There are essentially no quality aggregates larger than 3/4-in. locally available in the Lower Red River Valley region. Therefore, three types of materials typical of those available from nearby sources were considered for use as the large aggregate for this study: 1) syenite from Arkansas, 2) sandstone from Arkansas, and 3) limestone from the Ohio River Valley. Syenite was chosen as the large aggregate for this study based upon the proximity of the quarry to the construction site and upon its thermal properties. The coefficient of linear thermal expansion was determined for samples of the three materials furnished by the Vicksburg District. A test method based on CRD-C 125-63 (U. S. Army Corps of Engineers, 1989), modified for use with a Perkin Elmer Thermomechanical Analyzer (TMS-1) was used. Tests were conducted on 0.224-in. diameter by 0.3-in. long cylinders over a range of temperatures from 30° C to 100° C (86° F to 212° F). The test results showed that the thermal expansion was linear over that range of temperature. The coefficients of linear thermal expansion (α) were as follows:

Mineral	Coeff. of Linear Thermal Expansion (α) per °C	per °F
Limestone	4.8×10^{-6}	2.7×10^{-6}
Syenite	6.0×10^{-6}	3.3×10^{-6}
Sandstone	10.8×10^{-6}	6.0×10^{-6}

13. The large aggregate is a crushed stone. It is a speckled medium light gray, medium to coarse grained igneous rock classified as a syenite. Its composition and textural characteristics are similar to those of granite. Physically, the stone is angular with rough surface texture. It appears to be structurally sound and durable and is free of potentially alkali-silica reactive constituents. The grading and other physical characteristics of the large aggregate are presented in Appendix I.

Cementitious Materials

14. The effects of a wide range of levels of blends of portland cement with Class C fly ash and curing conditions on strength development, heat of hydration, and time of setting were studied using small mortar specimens. This relatively inexpensive investigation was conducted prior to the mixture proportioning study to avoid the large expense necessary to study the performance characteristics of trial concrete mixtures over wide range of mixture proportions. Compressive strength, heat of hydration, and time-of-setting properties of mortars are not usually directly interpretable into quantitative performance characteristics of concretes. However, the relative effects of changing substitution levels on these properties should be about equivalent. Therefore, the results of this work were used to evaluate the potential for change in the performance of concrete mixtures as cementitious material proportions were varied. The testing reported in this report is a part of a more thorough cementitious materials investigation conducted by WES documented by Poole, et al (in draft).

Chemical and Physical Properties

15. At the time this work was initiated, the cement supplier for Locks and Dams 3, 4, and 5 had not been determined. However, WES was directed by the Vicksburg District to assume Type II, low alkali (LA), ASTM C 150 (ASTM, 1989) cement meeting the heat-of-hydration requirement at seven days (HH) would be used in the structure. Based on previous experience, a Type II, LA, HH cement manufactured by Lone Star Cement Company, Cape Girardeau, Missouri, was chosen for this investigation because this cement will probably be comparable to cements likely to be used by a contractor in the structures. Chemical and physical properties of this cement are given in Appendix I.

16. A Class C fly ash as per ASTM C 618 (ASTM, 1989) produced by Gifford-Hill, Boyce, Louisiana, was similarly chosen as the most likely fly ash for the project. Chemical and physical properties of this material are given in Appendix I.

17. The cement and fly ash were blended to achieve ratios (by volume) of Class C fly ash to total cementitious materials (F/C ratio) varying from 20% to 70%. Strength and heat of hydration were measured versus time. Setting

properties were quantitatively described for selected mixtures. The effect of elevated temperature on strength development, heat of hydration, and time of setting was investigated for selected mixtures.

Strength Development

18. Mortars were prepared and cast in cube molds in accordance with ASTM C 311 (ASTM, 1989). The cubes were cured in sealed plastic bags at the indicated temperatures. Compressive strength was measured in accordance with ASTM C 109 (ASTM, 1989), with three cubes broken at each test age (2, 7, 28, and 90 days).

19. The results of the compressive strength tests for specimens cured at room temperature (73°F) are shown in Figure 1. At test ages of 2 and 7 days, the compressive strengths days were reduced in linear proportion to the amount of fly ash in the blend over the observed range of F/C. At 2 days approximately 28 psi (11.3% of control) was lost for each one percent increase in F/C. At 7 days approximately 37 psi (8.9% of control) was lost for each one percent increase in F/C.

20. At test ages of 28 and 90 days (for specimens cured at 73°F), the relationship between strength and F/C ceased to be linear. Strengths at 28 days for F/C ratios of 20 and 30 percent closely approximated the strength of the control specimens without fly ash. For high F/C ratios the strengths of the mortars continued to be below that of the control specimens.

21. The contribution of the fly ash to the strength of the mortar was estimated assuming that the portland cement contributed in proportion with its volume. A bar chart showing comparisons of compressive strengths is shown in Figure 2. For example, if the fly ash in a mixture with an F/C ratio 20 percent had no effect on strength, the mixture should have at least 80 percent of the strength of a 100 percent portland cement specimen. All comparisons are for specimens cured at 73°F.

22. At all F/C ratios (20, 30, 40, 50, 60, and 70%), the fly ash causes some retardation in the 2-day strength relative to that expected from the portland cement fraction. However, by 7 days, this effect appears to be overcome for F/C ratios less than 70%, and the fly ash appears to be making a positive contribution to compressive strength. All apparent negative affects of the loss in portland cement volume have essentially disappeared by 28 days

for F/C ratios less than 70%.

23. By 90 days, the fly ash appears to make a significant contribution to compressive strength for all F/C ratios observed. At higher F/C ratios (50% or greater) the blended portland cement-fly ash mortar strengths are approximately 100% greater than the strength expected from the portland cement fraction alone.

24. In summary, it appears that the Class C fly ash causes a reduction in strength for ages less than approximately 7 days for most reasonable levels of F/C ratios. Between 7 and 90 days, impressive strength gains were obtained by the portland cement-fly ash mortars when compared to the strength expected from the portland cement fraction alone, indicating that the fly ash makes a significant contribution to compressive strength in that time frame.

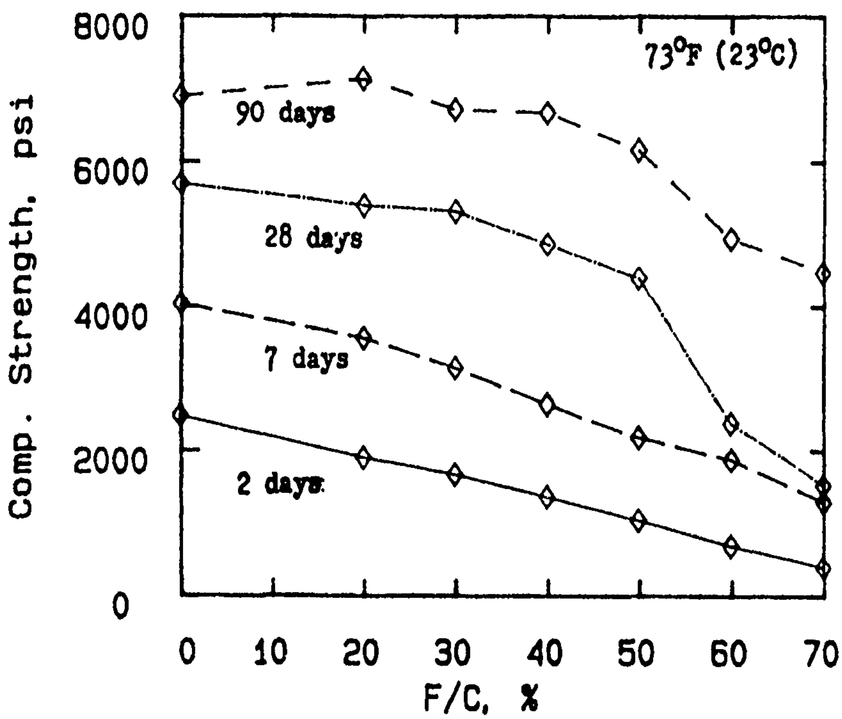

Figure 1. Compressive Strength of Mortar Cubes

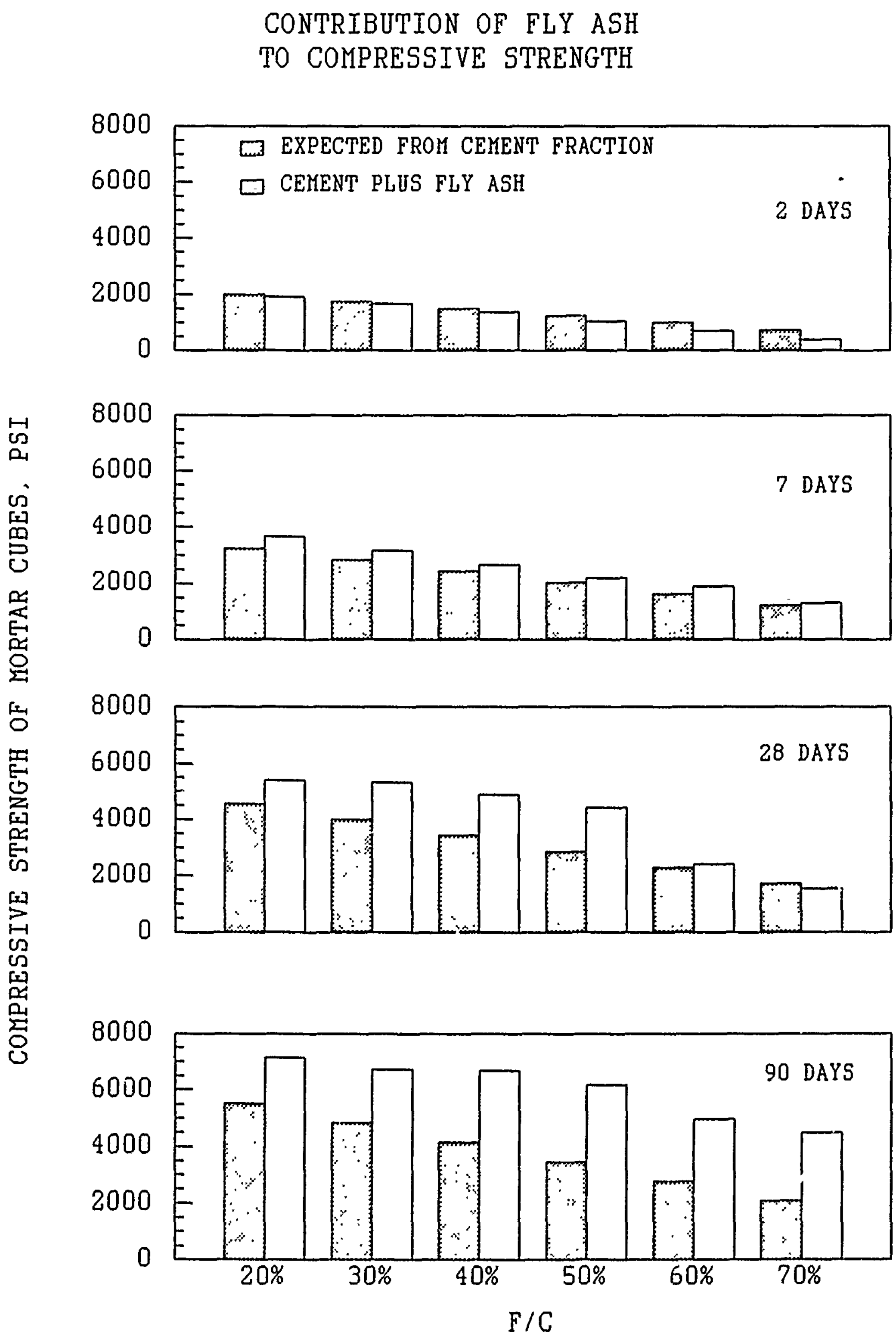

Figure 2. Contribution of Fly Ash to Compressive Strength of Mortar Cubes

Heat of Hydration

25. The heat of hydration was determined according to ASTM C 186 (ASTM, 1989). Single determinations were made at each age (1, 3, and 7 days). The data from these tests are shown in Figure 3.

26. The reduction in the heat of hydration due to use of Class C fly ash is linearly related to the F/C ratio at 1, 3, and 7 days. At 1 day the heat of hydration is close to that expected by the mass percent of portland cement in the mixture. This would indicate that the effect of the fly ash on heat evolution at early ages is largely due to the dilution if the portland cement. By 3 days the fly ash appears to make some detectable contribution to the heat generation. At 7 days, total the heat evolved by the mixtures was very close to the heat evolved by pure portland cement. Thus it appears that the Class C ash causes a substantial reduction in heat at early ages (before 7 days), but by 7 days no substantial reduction in heat of hydration is realized. This agrees well with the strength gain data above which indicate that by 7 days the fly ash is making a significant contribution to compressive strength over the range of feasible F/C ratios.

Time of Setting

27. Time of setting was determined according to ASTM C 191 (ASTM, 1989). Figure 4 presents the results of these tests. As expected, an increase in both initial, and final time of setting time was observed for the higher F/C ratios. The initial time of setting was increased some 20 percent, while the time of final setting was increased by approximately 28 percent. However, the effect of F/C ratio on initial and final times of setting was not well understood.

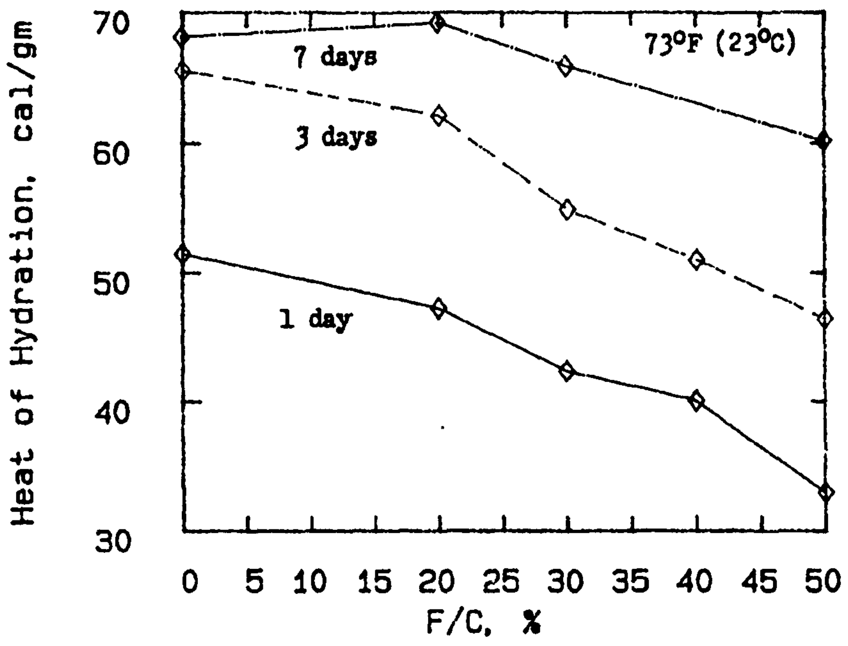

Figure 3. Heat of Hydration of Blended Materials at 1, 3, and 7 Days

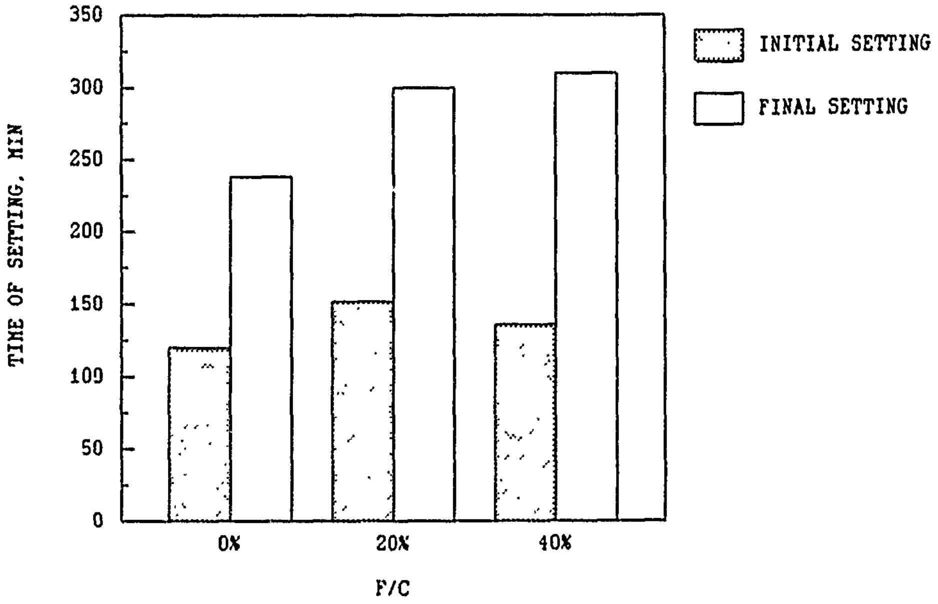

Figure 4. Time of Setting of Mortar Specimens by Vicat Method

PART III: MIXTURE PROPORTIONS SELECTION

Project Requirements

28. The major considerations in the selection of mixture proportions for a mass concrete structure are strength, durability, heat generation, and placeability. The specific requirements for this study were set by the Vicksburg District. These requirements are discussed below.

Strength

29. The majority of the concrete in the structures will have a design strength requirement based upon service conditions of 3000 psi. The exceptions to this will be the post-tensioned concrete in the trunnion girder anchorage and the baffle blocks in the stilling basin, which will have a design strength of 5000 psi. These requirements for various features of the structures are tabulated in Table 1.

30. In addition to design strength requirements, a strength requirement of 500 psi at time of erection of the forms for the next lift (5 to 7 days, typically) has traditionally been necessary for constructability considerations. This requirement is based upon form-anchorage requirements. At strengths of less that 500 psi, special formwork anchorages may be required, thus increasing construction effort and corresponding costs.

Durability

31. Durability is the capacity of concrete to resist the processes of deterioration including freezing and thawing or other weathering action, abrasion, chemical attack, etc. The durability of the concrete is enhanced by requiring the use of a low water-cement ratio and air-entrainment. The upper 1.5 feet of the dam wier (ogee) section of the dam and the stilling basin are required to have a maximum water-cement ratio of not more than 0.45 (by mass). The majority of the concrete above the minimum pool elevation is required to have a maximum water-cement ratio of 0.50, while the majority of concrete which will remain permanently submerged is required to have a maximum water-cement ratio of 0.65. The required water-cement ratios for various components of the structures are given in Table 1.

Table 1. Concrete Strength and Durability Requirements

Location	Feature	Minimum Strength, psi	Maximum Water-Cement Ratio (by Mass)
Dam	Foundation	3000	0.65
	Piers	3000	0.50
	Pier Bases		
	Top 1.5 ft.	3000	0.45
	Remaining Concrete	3000	0.65
	Stilling Basin		
	Top 1.5 ft.	3000	0.45
	Remaining Concrete	3000	0.65
	Baffle Blocks	5000	0.45
	Trunnion Girder and Anchorage	5000	0.50
Lock	Foundation	3000	0.65
	Floor	3000	0.65
	Walls		
	Above minimum pool	3000	0.50
	Below minimum pool	3000	0.65

Heat Generation

32. Early heat generation will be limited through the use of reduced quantities of cementitious materials and, to a lesser extent, the use a Class C fly ash as a portion of the cementitious materials.

Placeability

33. The placeability of concrete is determined by its workability and consistency. The concrete must have enough workability to be placed, consolidated, and finished properly without harmful segregation. The ease with which the concrete will flow during placement is its consistency. Placeability is measured by the slump of the fresh concrete as determined in accordance with ASTM C 143 (ASTM, 1989). The average slump for mass concrete should be approximately 2 in.

Preliminary Mixtures

34. Based upon the stated requirements, a matrix of preliminary mixtures was established. This matrix is shown in Figure 5. The matrix included water-cement ratios ranging from a minimum of 0.45 to a maximum of 0.65 based on a mass of portland cement having an absolute volume equivalent to that of the cementitious materials in the mixtures. The ratios (by volume) of fly ash to total cementitious materials (F/C ratio) were varied from a minimum of 25% to a maximum of 60%.

35. As with any mixture proportioning study, due consideration was given to the economy of the mixtures. The estimated cost of cementitious materials and admixtures was calculated based upon current prices for materials at potential project material sources. This information is shown in Figure 6. Each mixture is ranked based upon the estimated cost. A ranking of "1" means the mixture is the most economical, while a ranking of "15" means the mixture is the least economical of the mixtures considered in this study. Aggregate costs were not available for inclusion in the estimate. However, these costs should be relatively constant for all mixtures and therefore should not significantly change the ranking of the mixtures.

36. The mixture proportioning study was conducted in two phases. In Phase I, Mixtures A1 through A11 were prepared in the laboratory in accordance with ASTM C 192 (ASTM, 1989). Tests were conducted on the fresh concrete to determine slump (ASTM C 143), unit weight in accordance with ASTM C 138, and air content (ASTM C 231). Cylindrical specimens (6-in. by 12-in.) were prepared according to ASTM C 192 and cured in a moist curing room meeting the specifications of ASTM C 511 until time of testing. Specimens were tested in unconfined compression at ages of 1, 2, 7, 14, 28, and 90 in accordance with ASTM C 39. Selected specimens were tested at an age of 180 days.

F/C (%)	.65	.60	.55	.50	.45
60					A15
50			A12	A13	A14
40	A1	A2	A3	A10	A11
33	A4	A5	A6		
25	A7	A8	A9		

WATER-CEMENT RATIO

Figure 5. Mixture Proportioning Study Matrix

F/C (%)	.65	.60	.55	.50	.45
60					8.32 (4)
50			7.97 (2)	8.66 (6)	9.50 (9)
40	7.93 (1)	8.15 (3)	8.92 (7)	9.74 (12)	10.61 (14)
33	8.46 (5)	9.04 (8)	9.61 (11)		
25	9.52 (10)	10.05 (13)	10.81 (15)		

WATER-CEMENT RATIO

Figure 6. Estimated Cost of Cement, Fly Ash, and Water Reducing Admixture (Dollars per Cubic Yard)

37. In Phase II, selected mixtures (Mixtures A1, A7, A10, and A11) were repeated for replication and Mixtures A12, A13, A14, and A15 were added to the test matrix to investigate higher F/C ratios. All fresh and hardened concrete testing in Phase I was repeated. The mixture proportions for the 15 mixtures are given in Appendix II.

38. The results of the fresh and hardened concrete tests conducted in Phases I and II are tabulated in Table 2. The results of the unconfined compression tests are shown graphically for each mixture in Figures 7 through 21. In these figures the compressive strengths for each batch of concrete put together from the mixture proportions are shown.

39. Because one of the primary objectives of this study was to proportion concrete mixtures to limit heat generation, it follows that the cementitious materials content of the mixtures should be as low as possible. However, as the cementitious materials content decreases, it becomes increasingly critical to have properly graded aggregates in order to have mixtures with adequate workability. It is likely that concrete mixtures with cementitious contents as low as some of the mixtures in this study would not have adequate workability to be placed by all available techniques, even with properly graded aggregates. The mixtures would, however, have adequate workability to be transported and placed by buckets and would consolidate with proper vibration procedures.

Table 2. Results of Tests on Fresh and Hardened Concrete.

Mixture designation	W/C (by mass)	F.A. %	Slump, in.	Unit wt lb.ft^3	Air Content %	Compressive Strength, psi				
						1 day	2 days	7 days	28 days	90 days
A1	0.65	40	3-1/2	142.0	5.6	170	285	620	1,285	3,130
A2	0.60	40	2-1/2	142.4	5.5	175	300	625	2,025	2,810
A3	0.55	40	2-1/2	144.4	5.1	220	370	825	1,835	3,440
A4	0.65	33	3	143.6	5.0	255	340	625	1,615	2,865
A5	0.60	33	3-1/2	144.4	4.9	255	420	725	2,060	3,450
A6	0.55	33	2-1/4	144.4	4.7	275	450	800	2,400	3,915
A7	0.65	25	3-1/4	143.2	5.1	260	450	840	2,210	3,255
A8	0.60	25	3	143.2	5.2	320	520	975	2,550	3,585
A9	0.55	25	2-1/2	144.8	5.3	420	635	1,180	2,920	4,225
A10	0.50	40	2-1/2	144.8	5.0	280	410	960	2,170	4,130
A11	0.45	40	2-1/2	144.8	5.3	305	555	1,285	2,860	5,030
A12	0.55	50	2-3/4	143.2	5.2	120	415	585	925	2,700
A13	0.50	50	3-3/4	144.8	5.0	160	395	675	1,155	3,125
A14	0.45	50	2-1/2	143.6	5.1	195	475	815	1,485	3,330
A15	0.45	60	3-3/4	143.2	5.5	100	325	615	1,045	2,150
A1R	0.65	40	2-1/2	141.2	6.1	120	415	585	925	2,400
A3R	0.55	40	3-1/4	144.0	5.2	160	395	675	1,155	3,450
A7R	0.65	25	2-1/4	142.8	5.4	195	475	815	1,485	3,010
A11R	0.45	40	3-1/4	144.4	5.6	100	325	615	1,045	4,850

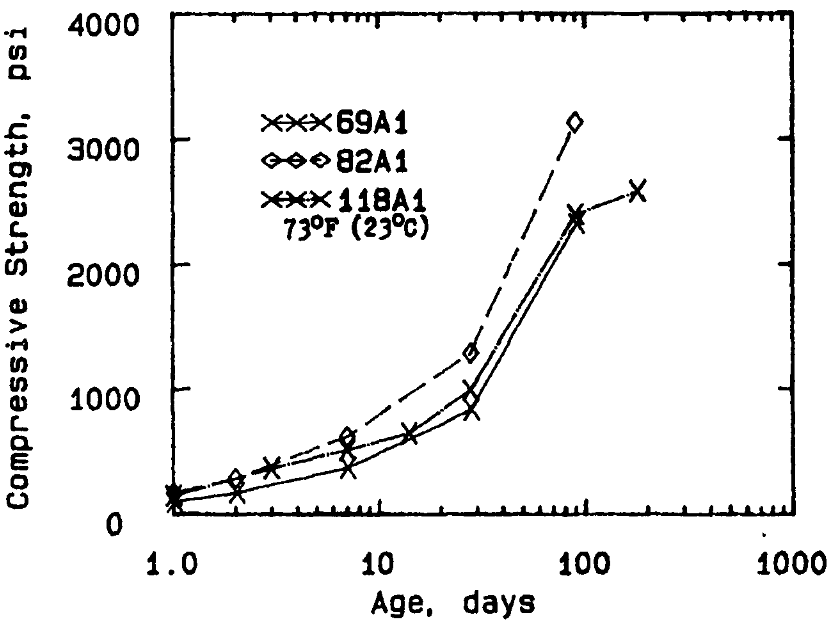

Figure 7. Compressive Strength Development, Mixture A1

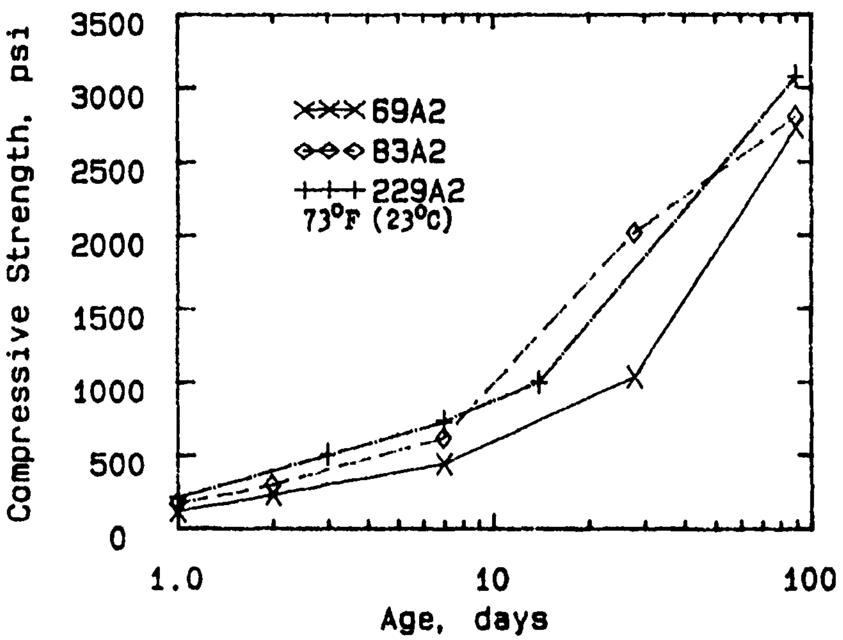

Figure 8. Compressive Strength Development, Mixture A2

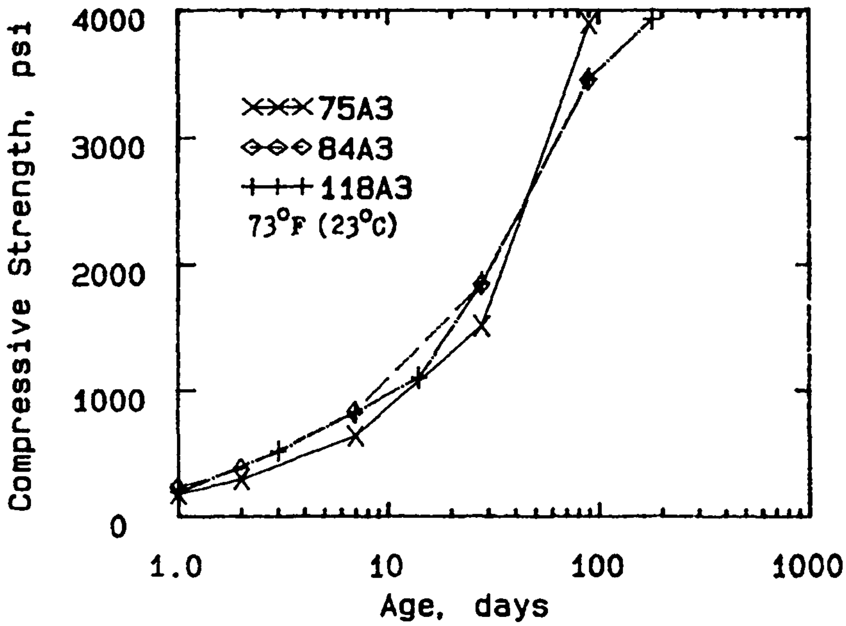

Figure 9. Compressive Strength Development, Mixture A3

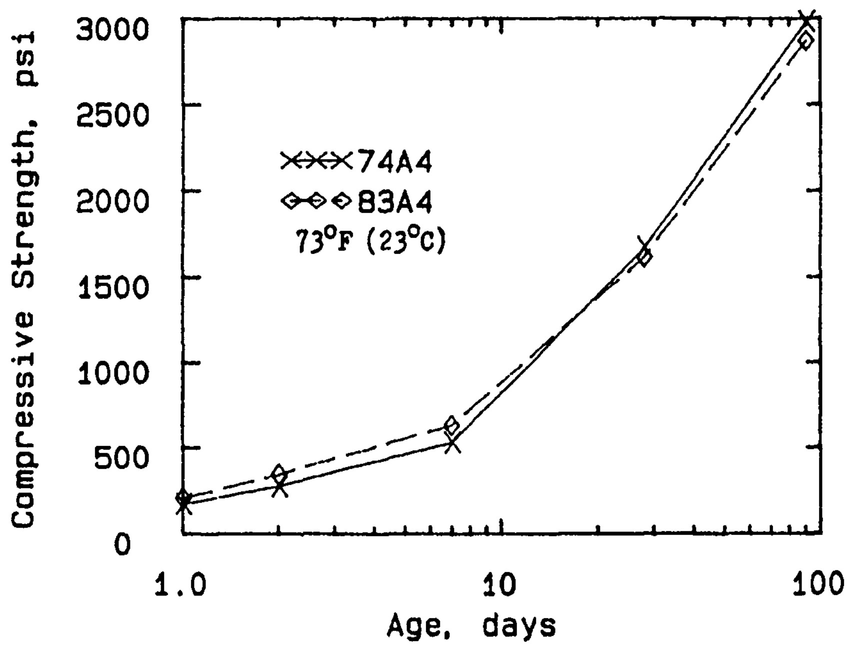

Figure 10. Compressive Strength Development, Mixture A4

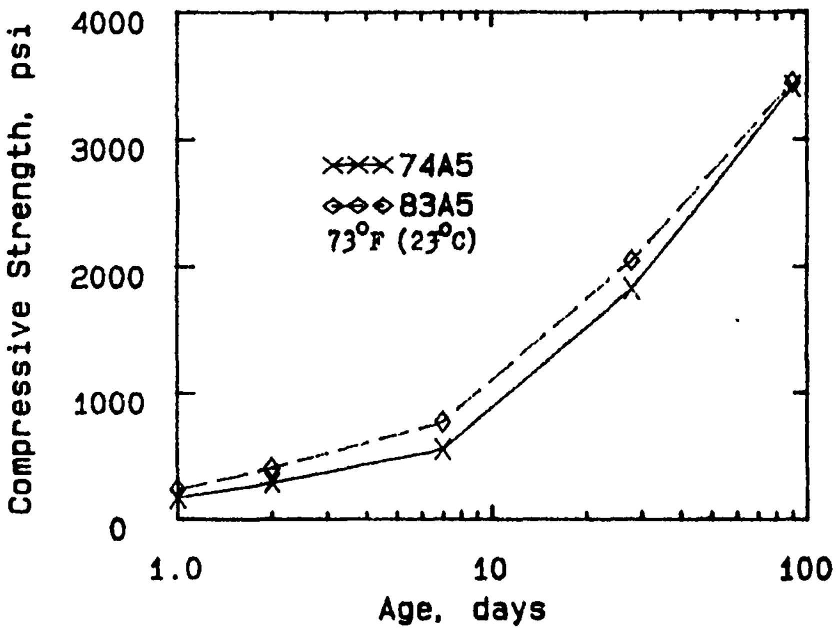

Figure 11. Compressive Strength Development, Mixture A5

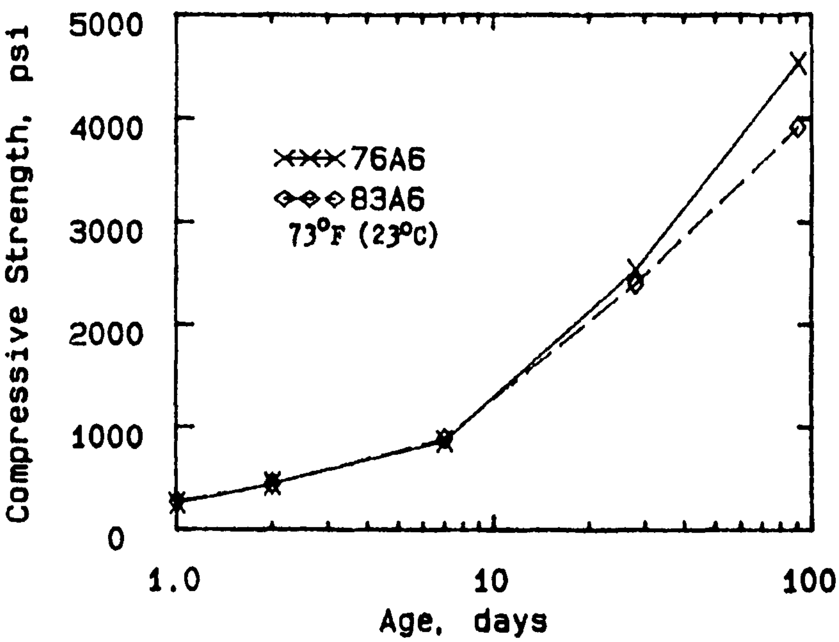

Figure 12. Compressive Strength Development, Mixture A6

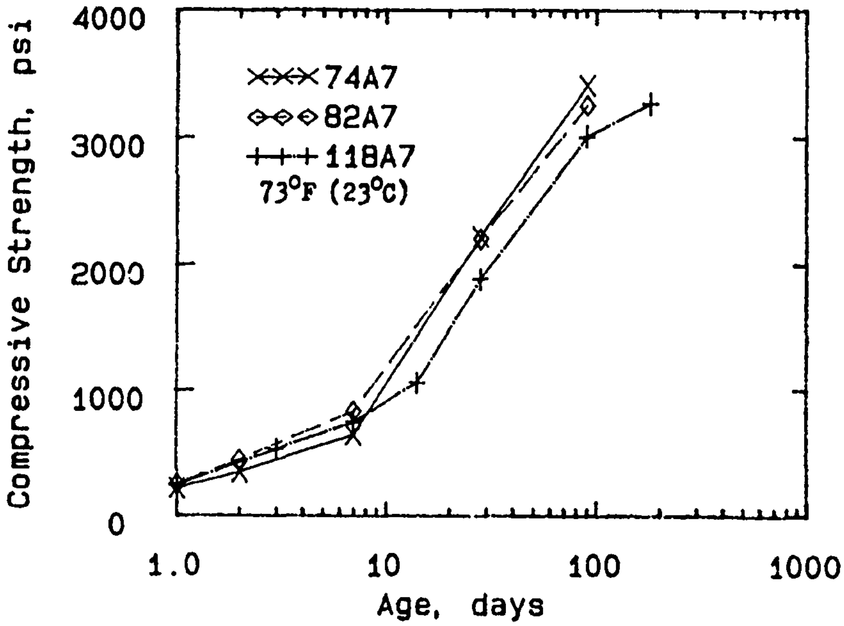

Figure 13. Compressive Strength Development, Mixture A7

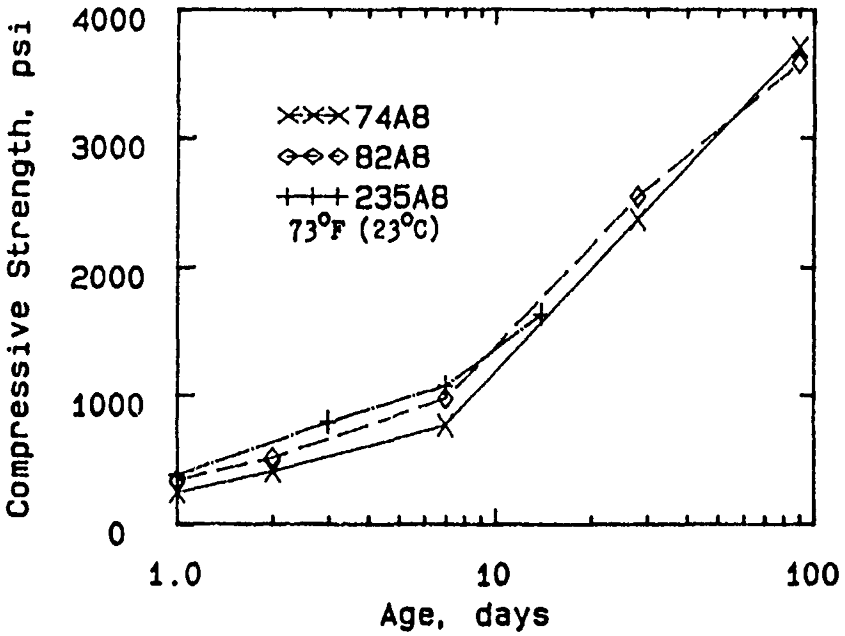

Figure 14. Compressive Strength Development, Mixture A8

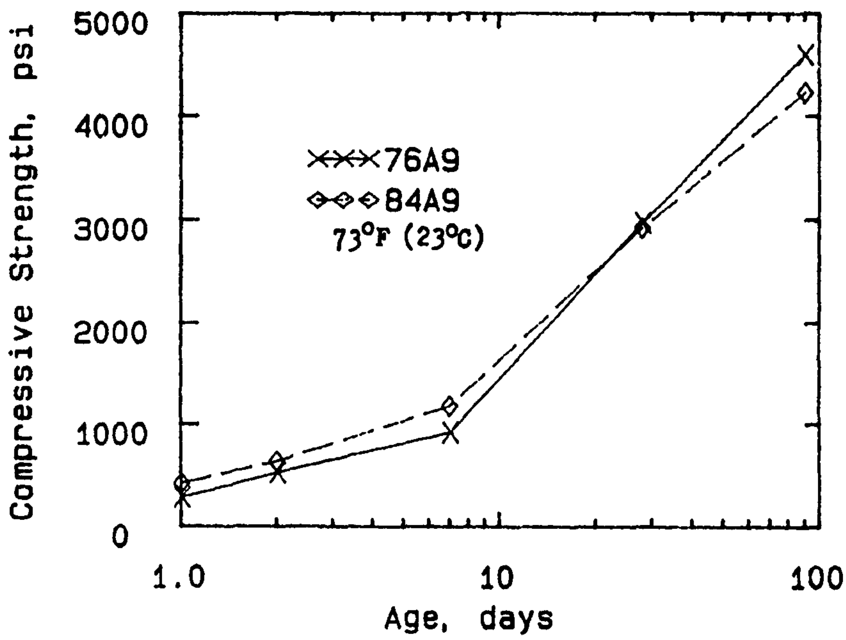

Figure 15. Compressive Strength Development, Mixture A9

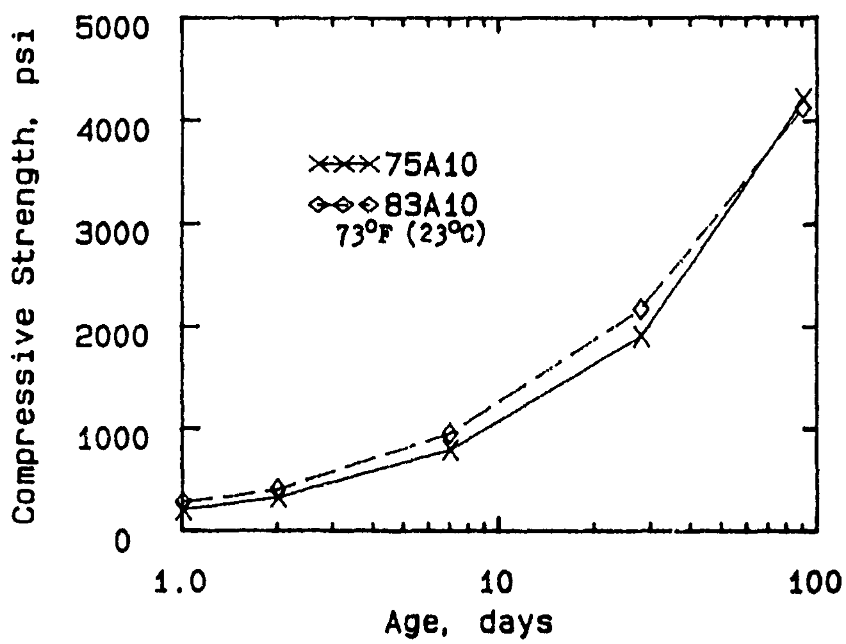

Figure 16. Compressive Strength Development, Mixture A10

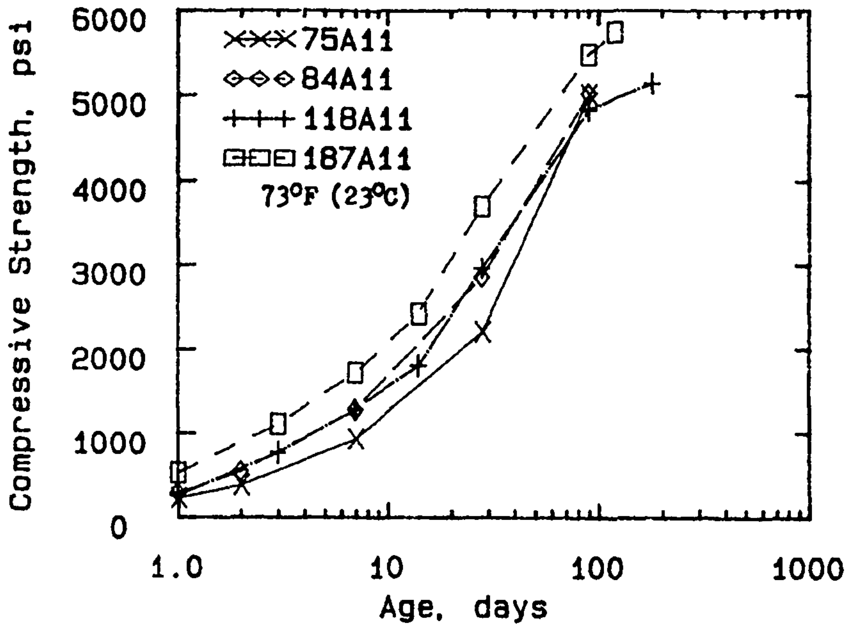

Figure 17. Compressive Strength Development, Mixture A11

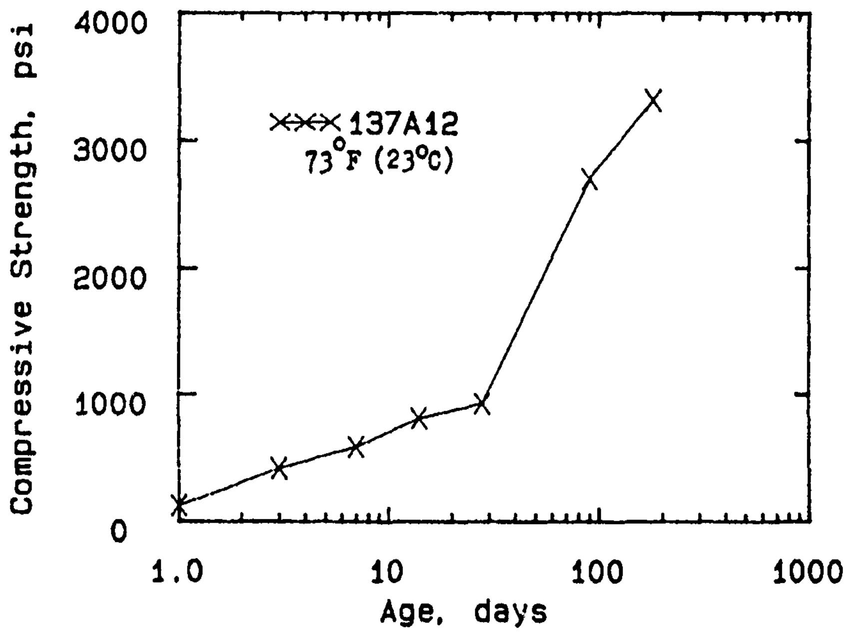

Figure 18. Compressive Strength Development, Mixture A12

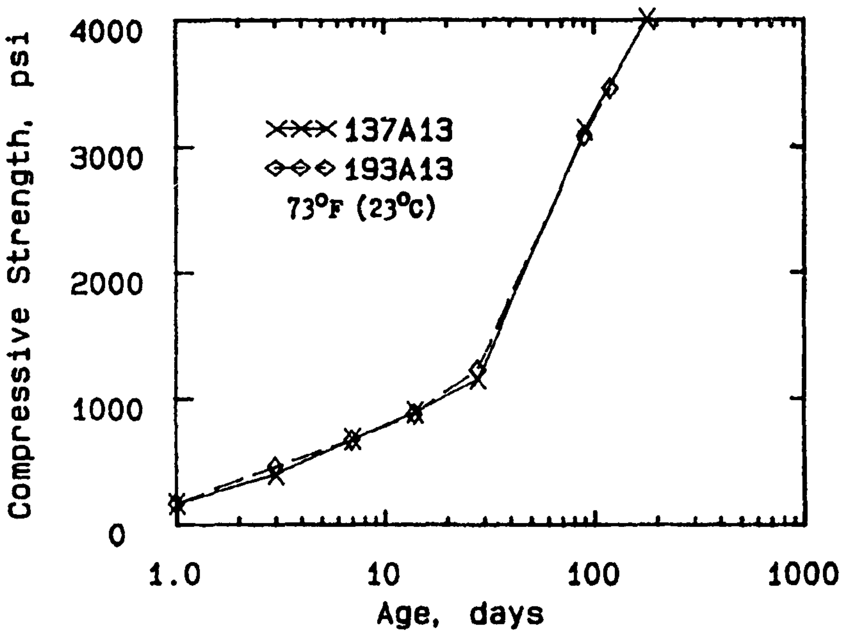

Figure 19. Compressive Strength Development, Mixture A13

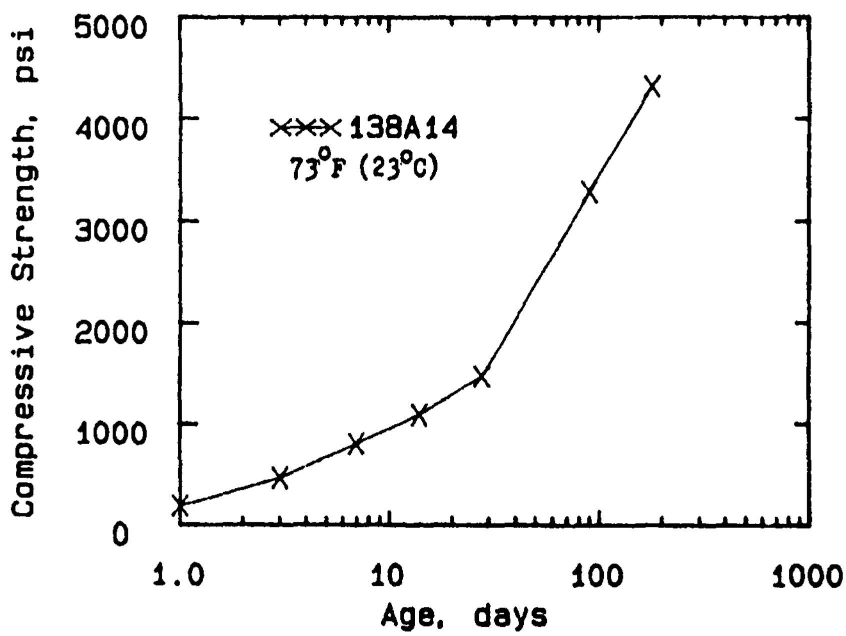

Figure 20. Compressive Strength Development, Mixture A14

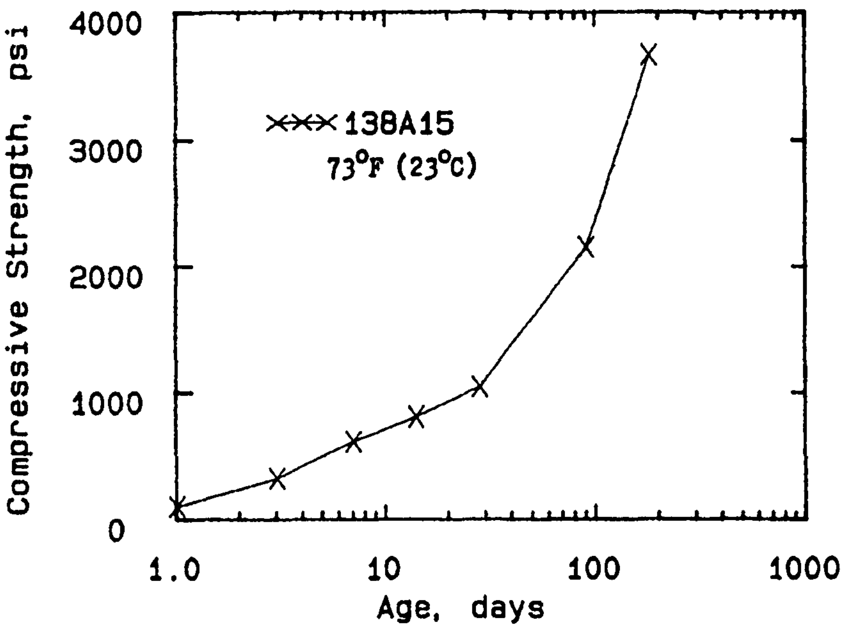

Figure 21. Compressive Strength Development, Mixture A15

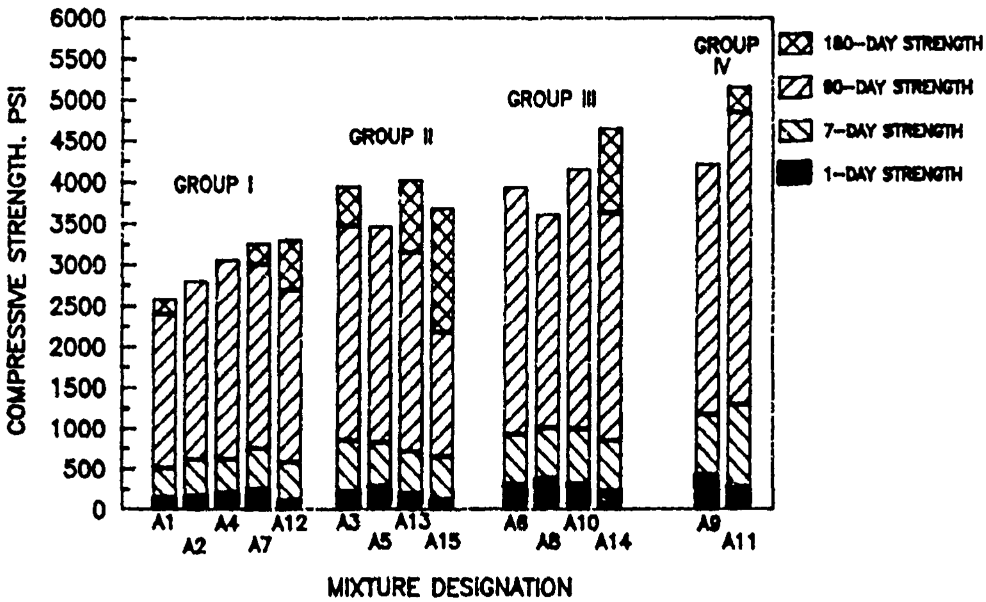

Figure 22. Compressive Strength by Groups

Final Mixture Selection

40. The data in Table 2 are summarized in Figure 22. Based upon the information from Phases I and II of the mixture proportioning study, the 15 trial mixtures were categorized in four groups as follows:

Group I	Group II	Group III	Group IV
A1	A3	A6	A9
A2	A5	A8	A11
A4	A13	A10	
A7	A15	A14	
	A12		

41. The mixtures in Group I are characterized by 5- to 7-day strengths judged to be too low to meet the strength criteria for form anchor considerations. The mixtures in Group II have marginal strengths, but may be acceptable in warm weather. The mixtures in Group III have adequate strengths at 73° F and should be evaluated using maturity concepts for cold weather applications. Group IV mixtures have excessive strength for mass concrete applications, but may be suitable for trunnion anchorages, ogee surfaces, stilling basins, etc. The compressive strengths obtained by mixtures in Group IV are similar to compressive strengths typically obtained by mass concrete mixtures used by the Vicksburg District.

42. Four mixtures (Mixtures A2, A8, A11, and A13) were selected for the full complement of thermal and mechanical properties testing. These mixtures cover the range of strengths deemed necessary for the project and will bracket the response of the remaining concretes at the higher levels of water-cement ratio and lower F/C ratios. The results of the thermal and mechanical properties tests are reported in Part IV of this report.

PART IV: MECHANICAL AND THERMAL PROPERTIES

General

43. The calibration and verification of the thermal and time-dependent material models used in the finite-element analyses requires the knowledge of certain key material response parameters. A series mechanical and thermal properties tests was conducted on the four selected mixtures (A2, A8, A11, and A13) identified in the mixture proportioning study. A description of the test methods and results are presented in this chapter. The use of these data to calibrate and verify the time-dependent material model will be reported in Report 2 of this series on the Red River Waterway Thermal Studies.

Mechanical Properties Investigation

44. A series of early-time material properties tests was conducted on hardened concrete specimens in support of the calibration and verification of the time-dependent material model used in the incremental-construction analysis. Specimens were prepared from Mixtures A2, A8, A11, and A13 for conducting compression tests and creep tests. All fresh concrete tests conducted as a part of Phases I and II of the mixture proportioning study were repeated. In addition, time-of-setting (TOS) tests were conducted in accordance with ASTM C 403 (ASTM, 1989). Creep tests were conducted at five ages of loading as necessary for the calibration and verification of the time-dependent material model. The ages of loading were chosen as TOS/2 + 12 hr., one day, three days, seven days, and 14 days.

Unconfined Compression Tests

45. Unconfined compression tests were conducted in accordance with ASTM C 39 (ASTM, 1989) at the ages shown above to provide data on strength as a function of time. The specimens tested were 6 in. in diameter by 12 in. in length. The ends of the specimens tested at ages of one day or less were capped with a neat cement cap, while the specimens tested at ages greater than one day were capped with sulfur capping compound. Capping of the ends of the specimens was necessary to provide plane and parallel loading surfaces in

accordance with ASTM C 39. The capped specimens were tested in a 440,000-lbf capacity universal testing machine by applying a uniaxial compressive force at 35 psi/sec until the specimen failed. The maximum recorded applied force was then divided by the original cross-sectional area to determine the unconfined compressive strength of the specimen. Figure 23 shows the results of these tests for the four mixtures as a function of age.

Compressive Creep Tests

46. Creep is most simply defined as time-dependent deformation due to sustained load. Although concrete can exhibit changes in deformation with no applied load due to shrinkage (both drying and sealed), creep is normally assumed to be the deformation in excess of shrinkage strains and elastic strains, as shown in Figure 24. Most researchers agree that the creep response of concrete is fundamentally governed by the movement of water and its effect on continued hydration and strength development. A brief discussion of the phenomena measured in a compressive creep test follows.

47. Upon initial application of load at time t_o (Figure 24), the material response is primarily elastic, but may include a non-elastic component. The nominal elastic strain is governed by the elastic modulus at time $t - t_o$. Because the elastic modulus is increasing with time (quite rapidly at early ages) the elastic component of strain decreases with time, labeled as "true elastic strain" in Figure 24. It is common practice to ignore this change in elastic modulus with time except for special applications. This phenomenon is quite important, however, in the calibration of the time-dependent material model in the thermal stress analyses. Shrinkage of the creep specimen is measured by monitoring the deformation of identically prepared unloaded specimens. Thus the creep strains are calculated from the total measured strains as follows:

$$\epsilon_{creep} = \epsilon_{total} - \epsilon_{elastic} - \epsilon_{shrinkage}$$

48. Using these concepts, creep tests were conducted according to ASTM C 512 (ASTM, 1989) modified to include continuous data acquisition by computer. The specimens tested were 6 in. in diameter by 16 in. in length. The

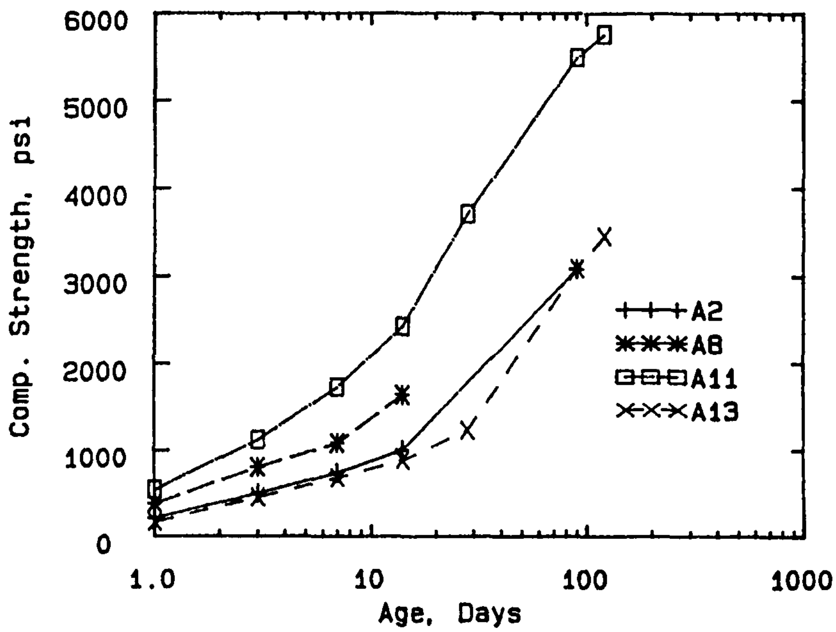

Figure 23. Compressive Strength Development, Creep Test Companion Cylinders

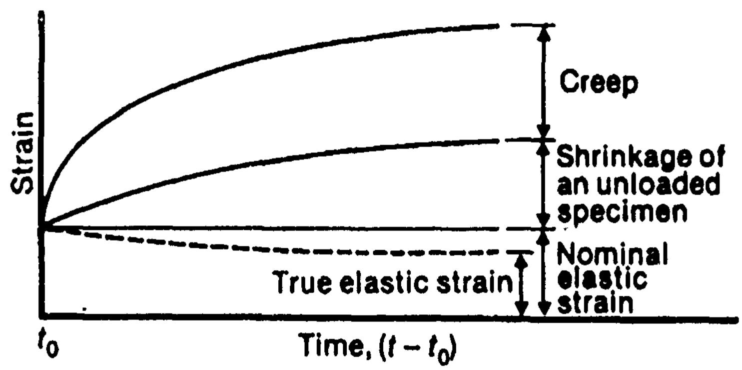

Figure 24. Response of Concrete to Sustained Load

creep specimens were cast in steel forms with the longitudinal axis horizontal. These forms accommodated Carlson strain gages placed at the center of the specimens oriented along the longitudinal axis of the cylinder. Steel bearing plates were attached to the ends of the specimen by embedded mechanical anchors. These plates provided a smooth plane surface for applying the compressive force. A bituminous moisture barrier was applied to the surface of the creep specimen immediately after the forms were removed to prevent moisture from entering or leaving the specimen.

49. The apparatus used to perform the creep tests was a hydraulic loading frame designed to maintain a constant stress by means of a gas pressure regulator in series with a gas/oil accumulator and hydraulic ram. The desired applied stress was set by means of the gas pressure regulator. The test device accommodated two specimens loaded in series. For each mixture two control cylinders were also monitored to determine the strains not associated with the applied loads. The creep specimens were loaded to 40% of the unconfined compressive strength at the age of loading as determined from unconfined compressive tests on companion 6-in. by 12-in. cylinders. The following measurements recorded using a digital data acquisition unit:

a. applied stress, by a pressure transducers located in the gas pressure regulator output line;

b. strain and temperature in the loaded specimen, by Carlson strain gages embedded in the center of the specimen;

c. strain and temperature in the control specimen, by Carlson strain gages embedded in the center of the specimen, and

d. time, by an internal clock in the computer data-acquisition unit.

50. Not all attempted tests were successful; each test is accounted for in Table 3.

51. The data from the valid tests were reduced as specified in ASTM C 512. The procedure requires that the strains which occur during the initial loading and the strains recorded by the shrinkage compensation cylinders be subtracted from the measured strains. These corrected strains were then divided by the average sustained stress to obtain creep strain per unit stress. It should be noted that the change in elastic strain which occurs due

to changes in the increase in elastic modulus with time is ignored by this procedure. However, in the calibration of the time-dependent material model this phenomena will be accounted for. These data are plotted for the four mixtures in Figures 25 through 28.

52. Several observations can be made about the creep data. As expected, the creep strain per unit stress decreases with increasing age of loading. This decrease of the creep response is related to the continuing hydration and strength-gain process. The specimens loaded at very early ages (1 day or less) exhibit high levels of creep very early after the application of the stress. This is due to the amount of free water which is able to move within the matrix at this early time in the hydration process.

53. The elastic modulus of the four mixtures at the various ages of loading was determined from the initial loading phase of the creep tests. Although at very early ages (three days or less) the mixtures exhibited limited linear elastic compressive behavior, estimates of elastic modulus at very early times are necessary for calibrating the time-dependent material model. Thus, a tangent modulus was determined from the stress-strain data obtained upon initial loading of a compressive creep specimen. This initial loading phase of the creep test was usually conducted in less than two minutes total elapsed time; however, some creep occurred during the initial loading phase, particularly at the earlier ages of loading. Any creep strains which occurred during the initial loading phase were subtracted from the elastic strains in calculating the elastic modulus.

54. The calibration of the time-dependent material model is improved by supplementing the elastic modulus data obtained at early time with data obtained at some time in excess of 28 days. These data were obtained by testing 6-in. by 12-in. compressive cylinders in accordance with ASTM C 469 (ASTM, 1989).

Table 3. Summary of Creep Tests

Mixture	Age at Loading	Applied Load, psi	Comments
A2	18 h	84	Strain gage output is questionable. Data are not shown.
	1 d	176	Strain gage output is questionable. Data are not shown.
	3 d	200	Good test. Data are shown in Figure 25.
	7 d	292	Good test. Data are shown in Figure 25.
	14 d	403	Good test. Data are shown in Figure 25.
A8	16 h	86	Good test. Data are shown in Figure 26.
	1 d	151	Data lost due to faulty relay board.
	3 d	318	Data lost due to faulty relay board.
	7 d	430	Good test. Data are shown in Figure 26.
	14 d	654	Good test. Data are shown in Figure 26.
A11	18 h	150	Good test. Data are shown in Figure 27.
	1 d	214	Good test. Data are shown in Figure 27.
	3 d	446	Good test. Data are shown in Figure 27.
	7 d	682	Good test. Data are shown in Figure 27.
	14 d	970	Good test. Data are shown in Figure 27.
A13	19 h	58	Good test. Data are shown in Figure 28.
	1 d	64	Data lost due to faulty relay board.
	3 d	181	Data lost due to faulty relay board.
	7 d	267	Good test. Data are shown in Figure 28.
	14 d	350	Good test. Data are shown in Figure 28.

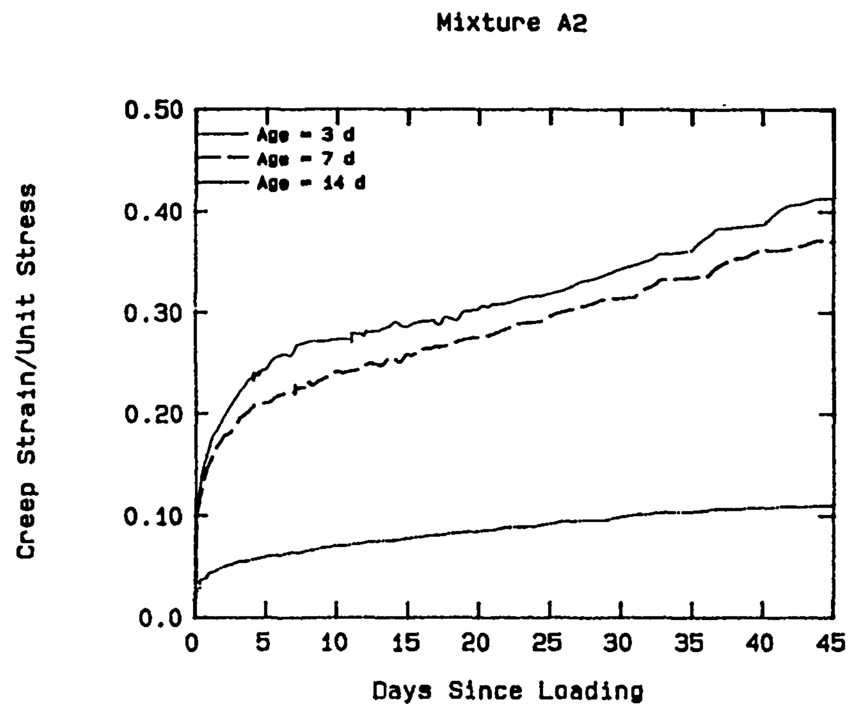

Figure 25. Creep Response, Mixture A2

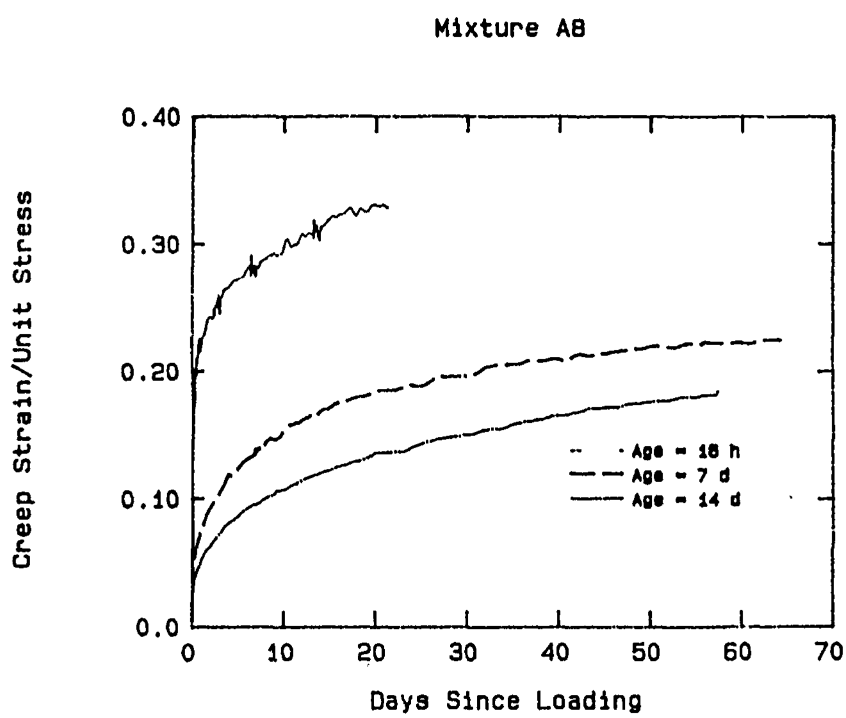

Figure 26. Creep Response, Mixture A8

Mixture A11

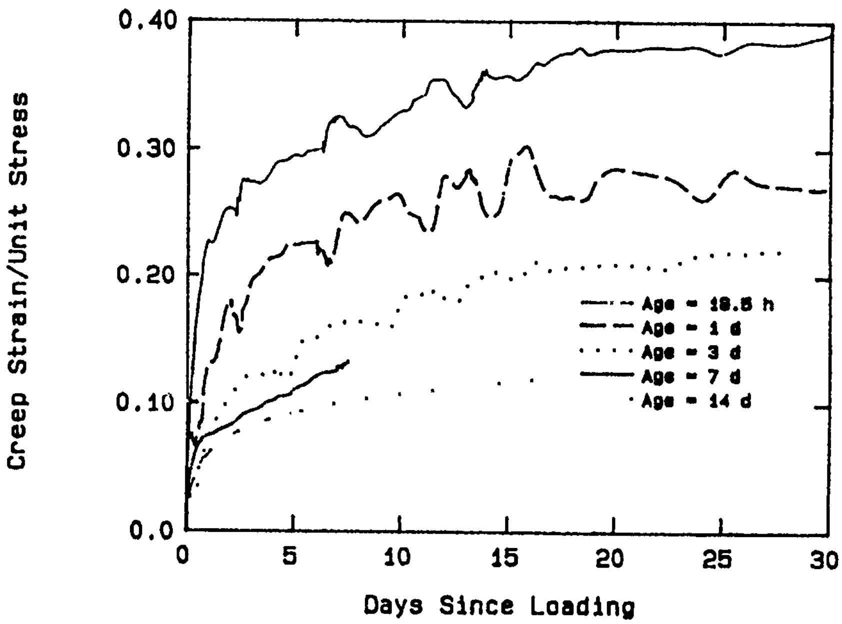

Figure 27. Creep Response, Mixture A11

Mixture A13

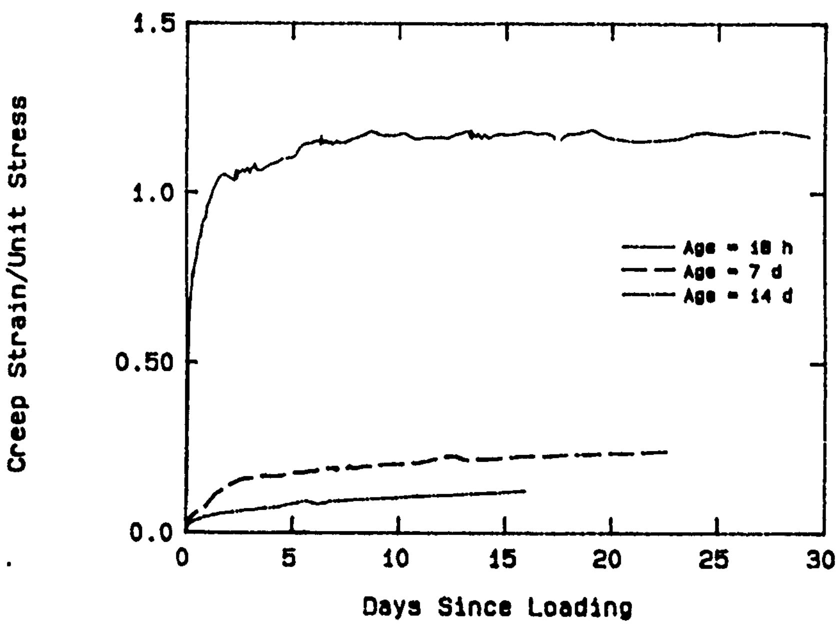

Figure 28. Creep Response, Mixture A13

55. The results of all modulus data are presented in Figure 29 in the modulus versus $\sqrt{f_c}$ plane. The ACI 318 formula (ACI. 1989) for modulus as a function of compressive strength

$$E = 57000\sqrt{f_c}$$

is also shown for purposes of comparison. These data indicate that the ACI formula is inadequate for predicting modulus for the present application. Also, the data indicate that all of the modulus data seem to fall along a straight line in this plane regardless of the fly ash replacement level or water-cement ratio. The exception to this observation, however, is Mixture A8. The modulus data from Mixture A8 appear to be in error in that the modulus is excessively high for such a low compressive strength. The cracking model is excessively sensitive to over-estimates in modulus, which lead unrealistic cracking in the analysis. Thus for purposes of model calibration, an estimate of the true modulus of the A8 mixture was needed. Using the method of least squares, the equation of a line was fitted to the modulus versus strength data for mixtures A2, A11, and A13. In Figure 30 these data are plotted along with the linear equation, given by

$$E = 103800\sqrt{f_c} - 380500$$

Thus knowing the compressive strength at a given age of loading, the modulus can be estimated with the above formula. In Figure 31, the modulus development of Mixtures A2, A11, and A13 along with the estimated modulus values for A8 is shown. These curves will be used to calibrate the time-dependent material model for the stress analyses.

<u>Sealed Length Change</u>

56. The change in length or volume of a concrete specimen sealed to prevent any drying shrinkage has been measured by a number of researchers. Experts do not agree on the mechanism that causes this phenomenon in the magnitudes observed. Some have attributed this change to "autogenous shrinkage", i.e., shrinkage due to chemical processes during the hydration process. Others believe that it may be due to moisture movement into the aggregate. However, in order to simulate the early-age material response properly, this volume-change phenomenon must be included in the material

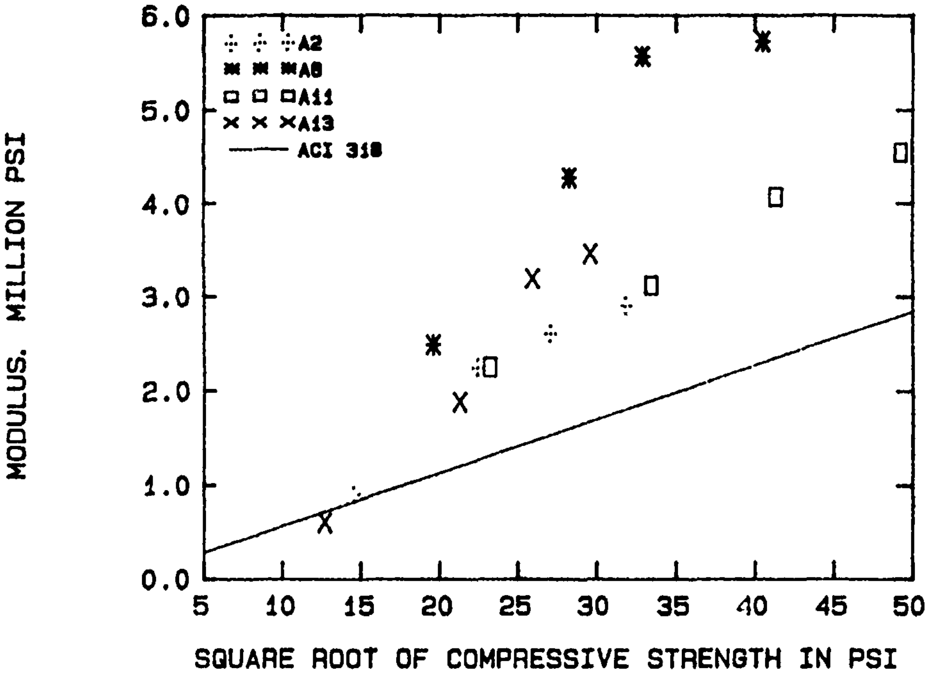

Figure 29. Relation Between Elastic Modulus and Compressive Strength

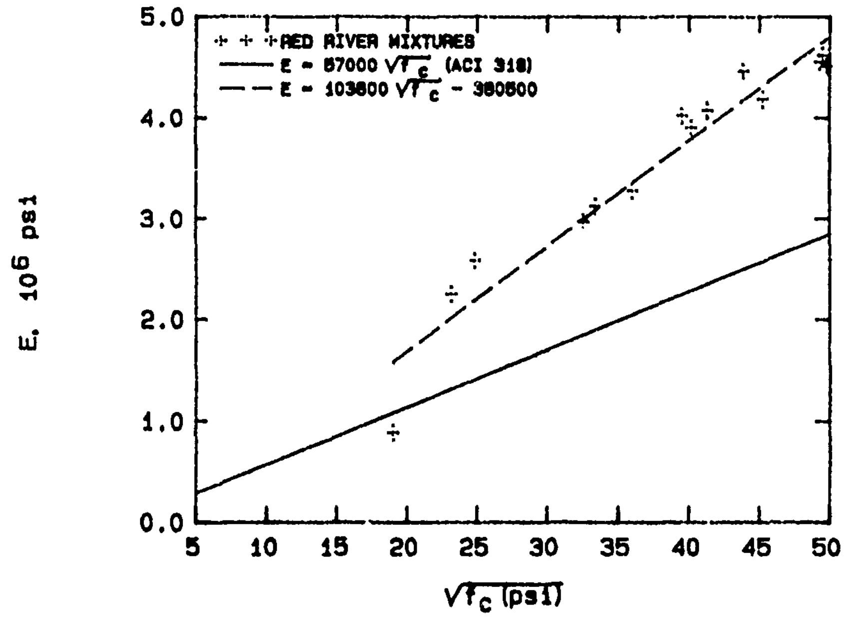

Figure 30. Determination of Formula for Elastic Modulus As a Function of Compressive Strength

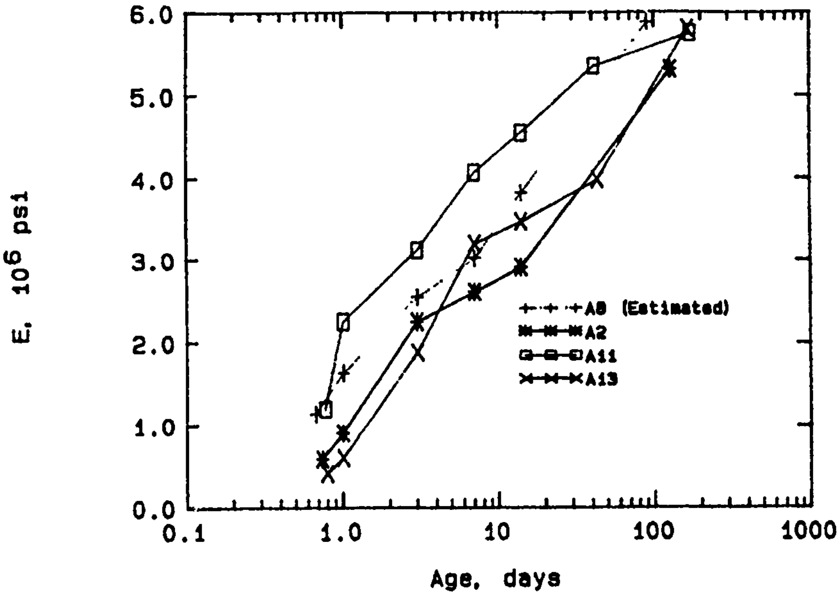

Figure 31. Elastic Modulus Development

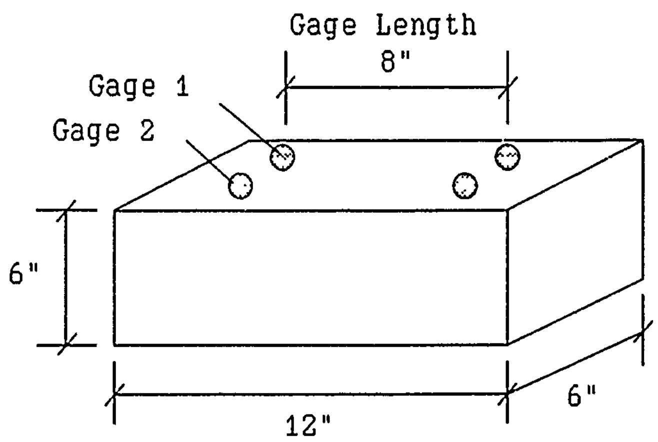

Figure 32. Geometry of Sealed Length Change Specimen

response model. In at least one instance (Hammons, et al, 1989) this change has been shown to be the predominant mechanism in early-age cracking of concrete used for resurfacing lock walls at Dashields Locks on the Ohio River.

57. Various techniques have been put forth in the literature for measuring the macroscopic effects of autogenous length or volume change (Slate and Matheus, 1967; Setter and Roy, 1978). For this study specimens were 6-in. by 6-in. by 12-in. rectangular prisms (Figure 32). Two sets of gage points were cast in place at two locations on the upper surface of the specimens with a gage length of approximately 8 in. Approximately 1 h after time of final setting the specimens were demolded and totally enclosed in a polyethylene vapor shield. The specimens were placed on a horizontal surface in a temperature-controlled laboratory. The change in length between the gage reference points was determined with a dial caliper at predetermined time intervals to determine length change values. Specimens were weighed periodically throughout the test program to insure that no moisture was lost to the surroundings.

58. The results of the autogenous length change measurements are shown in Figure 33. The curves shown in the figure are the average values of four measurements made on two specimens of each mixture. By comparing the data from Mixtures A2 and A8 (water-cement ratio of 0.60 for both mixtures), it appears that sealed length change decreases with increased F/C ratio. Similarly, by comparing Mixtures A2 and A11 (F/C ratio of 40% for both mixtures), it appears that sealed volume change decreases with increased water-cement ratio. Thus, at least for the cementitious materials used in this study, sealed volume change should be decreased by using a high water-cement ratio and a high level of fly ash replacement. It also appears that, at least for Mixtures A8, A11, and A13, the mixtures approach the same ultimate sealed length change of approximately 100 millionths. This would seem to indicate that the ultimate sealed length change is more dependent on the cement, pozzolans, and aggregates used in the mixtures than it is on the ratios or proportions of the constituents in the mixture. It should be noted that sealed volume change data obtained for a similar thermal study for Mississippi River Lock and Dam 26R (Bombich, etal, 1987) show that the magnitudes of sealed volume change for a L&D 26R mixture with a comparable

cement, F/C ratio of 25% (Class F fly ash), and limestone aggregate was approximately 2/3 greater than the magnitudes measured for this study.

Thermal Properties Investigation

Adiabatic Temperature Rise

59. Tests were conducted on each of the four selected concrete mixtures to determine the adiabatic temperature rise. Two similar adiabatic calorimeters were used in the investigation. Each calorimeter was basically an insulated container with a heat source and temperature controller which maintained near adiabatic conditions. A brief discussion of the test procedures and results follows.

60. A concrete specimen weighing 20 - 25 lb. was placed in a one-gallon metal container and sealed on top with the lid. The concrete-filled container was then placed onto a baseplate in the middle of the calorimeter. The container was in contact with a thermocouple (accurate to $\pm 0.1°F$) glued onto he underside of a spring-loaded copper sheet at the center of the baseplate. In order to provide good thermal contact, a thermal conducting paste was placed at the contact point between the container and the copper sheet-thermocouple assembly. The specimen was completely isolated from the surrounding ambient conditions by a well-insulated cover. An air-filled gap was provided between the inner wall surrounding the concrete-filled container and the insulated outer wall. Also an air-filled gap existed underneath the concrete-filled container. The temperature of the air in these gaps was constantly controlled by a heat source, and the air was circulated by a fan. A second thermocouple (accurate to $\pm 0.1°F$) placed in the air-filled gap was also connected to the heater controller, which maintained the temperature difference between the specimen and the air surrounding it near zero. With the thermal loss to the surroundings minimized, the continuous increase in specimen temperature was the adiabatic temperature rise. The temperature of the concrete was measured at two locations on the specimen container using thermistors (accurate to $\pm 0.01°F$). One thermistor was placed next to the thermocouple at the bottom of the container, and the other thermistor was placed at half height on the side of the container. Thermal conducting paste

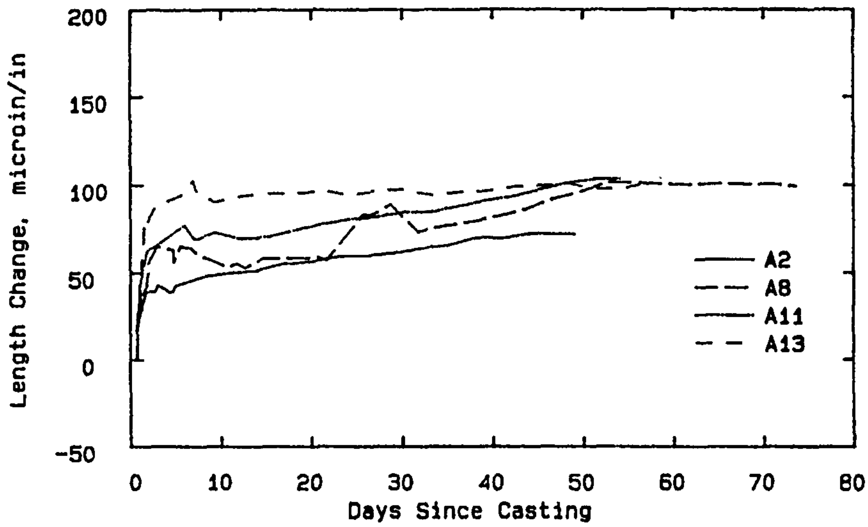

Figure 33. Sealed Length Change

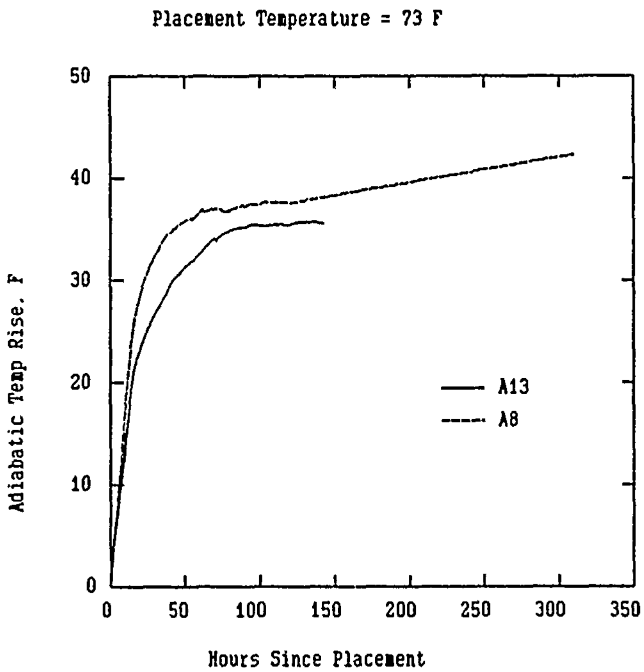

Figure 34. Adiabatic Temperature Rise

was used to insure good thermal contact between the thermistors and the concrete-filled container. The temperature was recorded continuously using a computer-controlled data acquisition system.

61. The results from the adiabatic temperature rise tests are shown in Figure 34. Due to errors in the calibration of the adiabatic calorimeter, the data from Mixtures A2 and A11 were in error and are therefore not shown.

Other Thermal Properties

62. The coefficient of linear thermal expansion, thermal diffusivity, specific heat, and thermal conductivity of concrete from mixtures A8 and A13 were determined at test ages of 3 and 28 days on laboratory molded specimens. The results of these tests are reported below.

63. The coefficient of linear thermal expansion was determined in accordance with CRD-C 39-81 (U. S. Army Corps of Engineers, 1989) at test ages of 3 and 28 days. Two 6-in. by 16-in. cylindrical specimens were cycled between water baths maintained at 40°F and 140°F. The strains in the specimens were measured with embedded Carlson strain meters. All data, including the temperatures of the water baths, were acquired and recorded with a digital data acquisition system and microcomputer. The results of the tests are tabulated in Table 4.

64. The thermal diffusivity of each of the two mixtures at test ages of 3 days and 28 days was determined in accordance with CRD-C 36-73 (U. S. Army Corps of Engineers, 1989) on 6-in. by 12-in. cylindrical specimens. However, the temperature of the hot and cold water baths were maintained at 140°F and 40°F, respectively, rather than maintaining the hot bath at a temperature of 212°F and the cold bath at essentially the temperature of the laboratory tap water as called for in the standard method. This range of temperatures was chosen because it is the likely range of temperatures expected in the mass concrete. The water bath temperatures were monitored with thermocouples. The specimen temperatures were monitored with thermocouples placed in the center of gravity of the cylindrical concrete specimens. All data were acquired and recorded using a digital data acquisition system and microcomputer. Two specimens of a given mixture were simultaneously alternated between the hot and cold baths. The specimens were allowed to remain in the bath until the temperature at the center of the specimen equilibrated with the bath

temperature. The results of the tests are tabulated in Table 4.

65. The specific heats of the two concrete mixtures were determined at ages of 3 and 28 days in accordance with CRD-C 124-73 (U. S. Army Corps of Engineers, 1989). However, as noted for the thermal diffusivity tests, the hot and cold water bath temperatures were maintained at 140°F and 40°F, respectively, rather than at 125°F and 35°F as prescribed in CRD-C 124. All temperatures were measured with thermocouples, and all data were acquired with a digital data acquisition system. The results of the tests are given in Table 4.

66. The thermal conductivity of the concrete was calculated in accordance with CRD-C 44-63 (U. S. Army Corps of Engineers, 1989). This method requires the results of the thermal diffusivity and specific heat tests as reported above. Also required is the actual unit weight of the concrete. This was determined by weighing the concrete specimens in air and water. The results of these calculations are shown in Table 4.

67. The average moisture contents of the specimens are also recorded in Table 4 for comparison and informational purposes.

68. As expected, there was very little variability in the diffusivity, specific heat, or thermal conductivity between the two mixtures or as a function of age. The variations noted are well within normally expected experimental scatter and cannot be interpreted as significant.

Table 4. Results of Thermal Properties Tests

Property	Units	Mixture A8 3-Day	Mixture A8 28-Day	Mixture A13 3-Day	Mixture A13 28-day
Coefficient of Linear Thermal Expansion	millionths per °F	5.68	5.48	5.34	5.72
Diffusivity	ft^2/h	0.0359	0.0360	0.0360	0.0358
Specific Heat	Btu/lb-°F	0.216	0.224	0.207	0.213
Thermal Conductivity	Btu/h-°F-ft	1.14	1.19	1.11	1.15
Unit Weight	lb/ft^3	146.6	147.9	148.8	150.5
Moisture Content	percent	4.01	5.12	3.93	4.78

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

69. The use of concrete mixtures with Class C fly ash somewhat reduces the heat generated in the concrete at ages less than 7 days compared to mixtures without fly ash. Mixtures with Class C fly ash lead to the generation of more heat at early ages than would be expected from a corresponding mixture with Class F fly ash. This effect may, however, allow higher ratios of Class C fly ash to total cementitious materials than would be possible with Class F fly ash due to accelerated strength gain in the first three to five days after placement. The strength gain during this period is critical for safe removal of formwork and anchorage of forms for subsequent lifts.

70. Magnitudes of creep strains recorded in this study were strongly dependent on the degree of hydration of the cement paste and the related quantity of free water and rate of compressive strength gain. The mixtures with higher levels of cement replacement with fly ash had over two times as much creep at ages of 14 days or less than those with less cement replaced with fly ash.

71. The measured magnitudes of sealed length change obtained in this study for mixtures with Class C fly ash appear to be less than the magnitude of sealed length change measured for similar concretes with Class F fly ash in similar studies. This should lead to a reduction in the tendency to crack.

72. A total of 15 trial mixtures at fly ash replacement levels varying from 25% to 60% and water-cement ratios varying from 0.45 to 0.65 were investigated. The compressive strength data from the trial mixtures were used to group the mixtures into four distinct groups. Group I mixtures were considered to have strengths too low for formwork considerations. Group II mixtures have marginal strengths, but may be acceptable for warm weather applications. Group III mixtures have adequate strengths for the project requirements. The mixtures in Group IV have excessive strengths for mass concrete applications, but may be suited for high-strength applications. The mixtures in Group III represent considerable cost savings in terms of cost of

cementitious materials over the mixtures typically used by the Corps for mass concrete construction in this region of the country. Unlike the mixtures used previously, these mixtures should yield compressive strengths adequate to meet the design strength requirements without being overly conservative. From the matrix of fifteen mixtures, four were selected for further thermal and mechanical properties testing.

73. Because the concrete mixtures were proportioned, at least in part, to limit the heat generated, the cementitious material content of the mixtures is low; therefore the workability of the mixtures may not be as good as those typically used for mass concrete construction. However, the mixtures proportioned in this study have adequate workability to the transported and placed by buckets and will consolidate satisfactorily if adequately vibrated.

74. The mechanical properties and thermal properties tests resulted in enough information to adequately calibrate the time-dependent material model and the thermal model for a few selected mixtures. The creep tests showed that the magnitude of creep strongly depends upon the degree of hydration of the cement paste, associated free water, and compressive strength developed. The values of specific heat, thermal diffusivity, and thermal conductivity of the mixtures were not significantly affected by the use of higher levels of fly ash replacement, as these are principally controlled by the aggregates used in the mixture.

Recommendations

75. We recommend that the thermal and time-dependent material models be calibrated and thermal stress analyses should be conducted using data from the following mixtures:

Mass Concrete: Spring start - Mixture A13
Fall start - Mixture A8

High-Strength Concrete: Spring and Fall start - Mixture All

76. The innovative use of high ratios of fly ash to total cementitious materials is a significant breakthrough in economy of construction and controlling heat generation. However, because contractors and field construction personnel lack experience with such mixtures, some resistance to

using them may be encountered. Therefore, we recommend that the final mixture portions and materials used in the field should be very similar to those used in the thermal stress analyses. Any changes in mixture proportions or materials (such as types of cements, fly ash, or aggregates) made in the field should be carefully evaluated to ascertain what effects these changes might have on early-age compressive strength, heat generation, and thermal- and shrinkage-related cracking. This will necessitate close cooperation between the field construction personnel and the district materials personnel. Every effort should be made to inform all concerned that use of these mixtures will result in significant materials savings, reduced maintenance costs, and increased service life, and hence reduced life-cycle costs.

77. We further recommend that buckets be used for the transportation and placing of the mixtures proportioned in this study. Care should be exercised to insure adequate vibration in keeping with good construction practice.

78. We also recommend that the mixtures used for construction should not have a compressive strength of less than 500 psi at time of application of loads to embedded formwork anchorages. The contractor should be informed of all parameters which would affect the design of the formwork and formwork anchorages including the possibility of concrete compressive strengths at 3 to 5 days of 500 psi. This will allow the design of formwork anchorages for this strength. No problems are anticipated if the concrete strength at time of loading the formwork anchorages is greater than 500 psi.

79. In most cases no service loads will be applied to the structure until approximately 6 months or more after the concrete is placed. The traditional practice of specifying the design strength at 28 or 90 days has led to structures with concrete strengths at one year of 1.5 to 2 times the specified design strength. Therefore, the design strength of the concrete should be specified at no earlier than 120 days, which will result a more economical structure with no compromise in structural integrity. Any atypical construction loads such as cranes or other heavy equipment applied to the structure prior to the concrete attaining its specified design strength should be carefully and deliberately evaluated to determine if the concrete strength is adequate to allow the structure to carry the required loads without sustaining damage.

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c. Designation C 44-63. "Method for Calculation of Thermal Conductivity of Concrete."

d. Designation C 124-73. "Method of Test for Specific Heat of Aggregates, Concrete, and other Materials (Method of Mixtures)."

e. Designation C 125-63. "Methcd of Test for Coefficient of Linear Thermal Expansion of Coarse Aggregate (Strain-Gage Method)."

APPENDIX I

CHEMICAL AND PHYSICAL CHARACTERISTICS OF CONCRETE CONSTITUENTS

TO:		FROM: STRUCTURES LABORATORY
Dean Norman Structures Laboratory	REPORT OF TESTS ON POZZOLAN LMK-4 AD-2	USAE WATERWAYS EXPERIMENT STATION ATTN: CEMENT AND POZZOLAN UNIT PO BOX 631 VICKSBURG, MISSISSIPPI 39180-0631

COMPANY: Gifford-Hill Fly Ash	BIN NO: single sample	TEST REPORT NO: WES-3C-88
LOCATION: Boyce, Louisiana	TONS REPRESENTED:	REPORT DATE: 31 March 1988
SPECIFICATION: ASTM C 618, Class C		
Contract No: Red River Waterway Thermal Study		DATE SAMPLED: 28 January 1988

TEST RESULTS OF THIS SAMPLE ☒ COMPLY ☐ DO NOT COMPLY WITH 7 DAY SPECIFICATION REQUIREMENTS

TEST RESULTS OF THIS SAMPLE ☐ COMPLY ☐ DO NOT COMPLY WITH 28 DAY SPECIFICATION REQUIREMENTS

$SiO_2 + Al_2O_3 + Fe_2O_3$ %	MgO %	SO_3 %	AVAILABLE ALKALIES % (a)(b)	POZZOLANIC STRENGTH % CONTROL (b)		AUTOCLAVE EXPANSION %	
REQUIREMENTS							
MINIMUM 70.0 (F)(N) 50.0 (C)		MAXIMUM 5.0 (C)(F) 4.0 (N)	MAXIMUM 1.50	MINIMUM 75		MAXIMUM 0.8	
TEST RESULTS							
56.0	4.8	2.2	* 1.28	* 123		0.08	

SAMPLE NO.	MOISTURE CONTENT %	LOSS ON IGNITION %	FINENESS 325 (45µm) SIEVE % RETAINED	% POINTS VARIATION FROM AVERAGE PREVIOUS 10	LIME POZZOLAN STRENGTH PSI (2-IN CUBES)	WATER REQUIREMENT % OF CONTROL	DENSITY Mg/m^3	DENSITY VARIATION FROM AVERAGE OF PREVIOUS 10, %
REQUIREMENTS								
—	MAXIMUM 3.0	MAXIMUM 6.0 (C)(F) 10.0 (N)	MAXIMUM 34	MAXIMUM 5	MINIMUM 900	MAXIMUM 105 (C)(F) 115 (N)	—	MAXIMUM 5
TEST RESULTS								
1	0.1	0.1	19	-	-	92	2.60	-

(a) OPTIONAL REQUIREMENT LABORATORY CEMENT USED: Lone Star, Cape Girardeau, MO

(b) 28 DAY TEST * LABORATORY LIME USED: Chemstone

REMARKS: SiO_2: 32.6; Fe_2O_3: 6.6; Al_2O_3: 16.8; CaO: 22.7

Toy S. Poole

Toy S. Poole
Chief, Cement and Pozzolan Unit

NOTE: THE INFORMATION GIVEN IN THIS REPORT SHALL NOT BE USED IN ADVERTISING OR SALES PROMOTION TO INDICATE EITHER EXPLICITLY OR IMPLICITLY ENDORSEMENT OF THIS PRODUCT BY THE U. S. GOVERNMENT.

WES FORM 1195, 1 SEP 84 REPLACES ENG FORM 6000-R, 1 MAR 72, WHICH IS OBSOLETE.

TO: Dean Norman, Structures Laboratory	REPORT OF TEST OF HYDRAULIC CEMENT LMK-4 RC-2	FROM: STRUCTURES LABORATORY USAE WATERWAYS EXPERIMENT STATION ATTN: CEMENT AND POZZOLAN UNIT PO BOX 631 VICKSBURG, MISSISSIPPI 39180-0631

COMPANY: Lone Star Industries	TEST REPORT NO. WES-4-88
LOCATION: Cape Girardeau, MO	DATE: 17 February 1988
SPECIFICATION: ASTM C 150, II, HH	DATE SAMPLED: 28 January 1988
CONTRACT NO:	PROGRAM: single sample

PROJECT: Red River Waterway Thermal Studies

TEST RESULTS OF THIS SAMPLE [XX] COMPLY [ ] DO NOT COMPLY WITH 7 DAY SPECIFICATION REQUIREMENTS

TEST RESULTS OF THIS SAMPLE [ ] COMPLY [ ] DO NOT COMPLY WITH 28 DAY SPECIFICATION REQUIREMENTS

SAMPLE NO.	1		SURFACE AREA, m^2/kg	356	
SiO_2, %	23.1		AUTOCLAVE EXP., %	0.07	
Al_2O_3, %	2.8		INITIAL SET, MIN (GILLMORE)	125	
Fe_2O_3, %	3.3		FINAL SET, MIN (GILLMORE)	215	
CaO, %	62.4		AIR CONTENT, %	11	
MgO, %	3.5		COMP. STRENGTH, 3 D, PSI	2530	
SO_3, %	2.8		COMP. STRENGTH, 7 D, PSI	3230	
LOSS ON IGNITION, %	0.8		COMP. STRENGTH, D, PSI	-	
INSOLUBLE RESIDUE, %	0.25		FALSE SET-PEN. F/I, %	-	
Na_2O, %	0.05		Heat of Hyd 1d, cal/g	51	
K_2O, %	0.70		Heat of Hyd 3d, cal/g	66	
ALKALIES-TOTAL AS Na_2O, %	0.51		Heat of Hyd 7d, cal/g	68	
TiO_2, %	0.18				
P_2O_5, %	0.05				
C_3S, %	53				
C_3A, %	2				
C_2S, %	26				
$C_3A + C_3S$, %	55				
C_4AF, %	10				
$C_4AF + 2C_3A$, %	15				

REMARKS

Toy S. Poole
Toy S. Poole
Chief, Cement and Pozzolan Unit

THE INFORMATION GIVEN IN THIS REPORT SHALL NOT BE USED IN ADVERTISING OR SALES PROMOTION TO INDICATE EITHER EXPLICITLY OR IMPLICITLY ENDORSEMENT OF THIS PRODUCT BY THE U.S. GOVERNMENT

WES FORM 1540 4 AUG 87 EDITION OF 1 SEP 84 IS OBSOLETE.

1989

STATE: LA	INDEX NO: 11	AGGREGATE DATA SHEET	TESTED BY: USAEWES
LAT.: 32	LONG.: 93		DATE: Feb 88

LAB SYMBOL NO.: IMK-4 S-10 TYPE OF MATERIAL: Natural Sand

LOCATION: Coushatta, LA. Pit is 1/4 mile west on LA Hwy 3163 from junction with US Hwy 84

PRODUCER: Cobb Industrial Corp., Coushatta, LA

SAMPLED BY: Vicksburg District

TESTED FOR: Lock and Dam No. 4 and No. 5, Red River

USED AT:

PROCESSING BEFORE TESTING:

GEOLOGICAL FORMATION AND AGE:

GRADING (CRD-C 103) (CUM. % PASSING):

SIEVE	3-6"	1½-3"	¾-1½"	#4-¾"	FINE AGG.
6 IN.					
5 IN.					
4 IN.					
3 IN.					
2½ IN.					
2 IN.					
1½ IN.					
1 IN.					
¾ IN.					
½ IN.					
⅜ IN.					
NO. 4					99
NO. 8					84
NO. 16					64
NO. 30					46
NO. 50					12
NO. 100					1
NO. 200					0
-200(a)					0
F.M.(b)					

(a) CRD-C 105 (b) CRD-C 104

TEST RESULTS

	3-6"	1½-3"	¾-1½"	#4-¾"	FINE AGG.
BULK SP. GR., S.S.D. (CRD-C 107, 108)					2.64
ABSORPTION, % (CRD-C 107, 108)					0.4
ORGANIC IMPURITIES, FIG. NO. (CRD-C 121)	—	—	—	—	1
SOFT PARTICLES, % (CRD-C 130)					—
% LIGHTER THAN SP GR 2.00 (CRD-C 122)					0
% FLAT AND ELONGATED (CRD-C 119, 120)					
WT AV % LOSS, 5 CYC $MgSO_4$ (CRD-C 115)					
L.A. ABRASION LOSS, % (CRD-C 117, 145) GRADING ___					
UNIT WT, LB/CU FT (CRD-C 106)					113.8
FRIABLE PARTICLES, % (CRD-C 142)					
SPEC HEAT, BTU/LB/DEG F. (CRD-C 124)					
REACTIVITY WITH NaOH (CRD-C 128): SC mM/L:					
RC mM/L:					

MORTAR-MAKING PROPERTIES (CRD-C 116)

TYPE ___ CEMENT, RATIO: ___ DAYS, ___ %, ___ DAYS, ___ %

LINEAR THERMAL EXPANSION, MILLIONTHS/DEG F. (CRD-C 125, 126):

ROCK TYPE	PARALLEL	ACROSS	ON	AVERAGE

MORTAR:

MORTAR-BAR EXPANSION AT 100F, % (CRD-C 123):		FINE AGGREGATE 3 MO.	6 MO.	9 MO.	12 MO.	COARSE AGGREGATE 3 MO.	6 MO.	9 MO.	12 MO.
LOW-ALK. CEMENT:	% Na_2O EQUIVALENT:								
HIGH-ALK. CEMENT:	% Na_2O EQUIVALENT:								

SOUNDNESS IN CONCRETE (CRD-C 40, 114):			FST	HW-CD	HD-CW
FINE AGG.	COARSE AGG:	DFE300			
FINE AGG.	COARSE AGG:	DFE150			

PETROGRAPHIC DATA (CRD-C 127):

The sand is pale yellowish orange. Chert is the primary constituent in the sizes larger than 2.36 mm (No. 8) and quartz is in the smaller sizes. The sand is composed of blocky, ellipsoidal and spherical particles. Chalcedony is present in the sand.

REMARKS:

WES FORM 6011-R
1 MAR 1969

STATE: LA	INDEX NO.: 31 (Suppl 1)	AGGREGATE DATA SHEET	TESTED BY: USAEWES
LAT.: 31	LONG.: 92		DATE: Feb 88

LAB SYMBOL NO.: LMK-4 G-5, S-3 — TYPE OF MATERIAL: Natural Gravel & Sand

LOCATION: Jena, LA, T8N, R2E, 1/2 Sec 5 & 8, LaSalle Parish

PRODUCER: Western Gravel Co., Jena, LA

SAMPLED BY: Vicksburg District

TESTED FOR: Lock and Dam No. 4 and No. 5, Red River

USED AT:

PROCESSING BEFORE TESTING:

GEOLOGICAL FORMATION AND AGE:

GRADING (CRD-C 103) (CUM. % PASSING):

SIEVE	3-6"	1½-3"	¾-1½"	No. 4-¾"	FINE AGG.
6 IN.					
5 IN.					
4 IN.					
3 IN.					
2½ IN.					
2 IN.					
1½ IN.			100		
1 IN.			94		
¾ IN.			76		
½ IN.			55		
⅜ IN.			44		
NO. 4			15		94
NO. 8			2		88
NO. 16					80
NO. 30					61
NO. 50					20
NO. 100					3
NO. 200					1
-200[a]			0		0
F.M.[b]					

(a) CRD-C 105 (b) CRD-C 104

TEST RESULTS

	3-6"	1½-3"	¾-1½"	No. 4-¾"	FINE AGG.
BULK SP. GR., S.S.D. (CRD-C 107, 108)			2.53		2.63
ABSORPTION, % (CRD-C 107, 108):			1.7		0.2
ORGANIC IMPURITIES, FIG. NO. (CRD-C 121)	—	—	—	—	
SOFT PARTICLES, % (CRD-C 130)					—
% LIGHTER THAN SP GR 2.40 (2.00) (CRD-C 122)			12.9		(0)
% FLAT AND ELONGATED (CRD-C 119, 120)			3.5		
WT AV % LOSS, 5 CYC $MgSO_4$ (CRD-C 115)					
L.A. ABRASION LOSS, % (CRD-C 117, 145) GRADING ___					
UNIT WT, LB/CU FT (CRD-C 106):			106.4		109.2
FRIABLE PARTICLES, % (CRD-C 142)					
SPEC HEAT, BTU/LB/DEG F. (CRD-C 124)					
REACTIVITY WITH NaOH (CRD-C 128): Sc, mM/L:					
Rc, mM/L:					

MORTAR-MAKING PROPERTIES (CRD-C 116)

TYPE ___ CEMENT, RATIO: ___ DAYS, ___ %, ___ DAYS, ___ %

LINEAR THERMAL EXPANSION, MILLIONTHS/DEG F. (CRD-C 125, 126):

ROCK TYPE	PARALLEL	ACROSS	ON	AVERAGE

MORTAR:

MORTAR-BAR EXPANSION AT 100F, % (CRD-C 123):		FINE AGGREGATE				COARSE AGGREGATE			
		2 MO.	6 MO.	9 MO.	12 MO.	3 MO.	6 MO.	9 MO.	12 MO.
LOW-ALK. CEMENT:	% Na_2O EQUIVALENT:								
HIGH-ALK. CEMENT:	% Na_2O EQUIVALENT:								

SOUNDNESS IN CONCRETE (CRD-C 40, 114):			F&T	HW-CD	HD-CW
FINE AGG.	COARSE AGG:	DFE300			
FINE AGG.	COARSE AGG:	DFF300			

PETROGRAPHIC DATA (CRD-C 127):

The gravel is pale yellowish brown chert composed of blocky, pyramidal, and tabular particles with rounded edges and corners. Chert was the major constituent of each sieve fraction larger than 9.5 mm (3/8 in.) with the remainder quartz and miscellaneous particles.

The sand is primarily chert in sizes larger than 2.36 mm (No. 8), with quartz and feldspar increasing in the smaller sizes. A trace of heavy minerals is present in the smaller sizes, as is chalcedony. Quartz content ranges from

REMARKS:

63% to 90% of the sizes passing the 1.18 mm (No. 16) sieve. Individual particles are blocky, tabular, spherical and ellipsoidal in shape.

ENG FORM 1 MAR 1966 6011-R

1988

STATE: AR	INDEX NO.: 12 Suppl3	AGGREGATE DATA SHEET	TESTED BY: USAE WES
LAT: 34	LONG: 92		DATE: March, 1986

LAB SYMBOL NO.: VICKS-33 MG-4 TYPE OF MATERIAL: Manufactured Gravel

LOCATION: Granite Mountain Quarry No. 1 - Frontage road, north of Dixie Road and each of Hwy 67 in Sweet Home, AR

PRODUCER: Granite Mountain Quarries, McGeorge Corp., Sweet Home, AR

SAMPLED BY: Vicksburg District

TESTED FOR: Yazoo Backwater Pumping Plant

USED AT:

PROCESSING BEFORE TESTING:

GEOLOGICAL FORMATION AND AGE:

GRADING (CRD-C 103) (CUM. % PASSING):

SIEVE	3-6"	1½-3"	¾-1½"	#4-¾"	FINE AGG.
6 IN.					
5 IN.					
4 IN.					
3 IN.					
2½ IN.					
2 IN.					
1½ IN.			100		
1 IN.			81		
¾ IN.			50		
½ IN.			31		
⅜ IN.			17		
NO. 4			3		
NO. 8			1		
NO. 16					
NO. 30					
NO. 50					
NO. 100					
NO. 200					
-200 (a)					
F.M. (b)					

(a) CRD-C 105 (b) CRD-C 104

TEST RESULTS	3-6"	1½-3"	¾-1½"	#4-¾"	FINE AGG.
BULK SP. GR., S.S.D. (CRD-C 107, 108)			2.64		
ABSORPTION, % (CRD-C 107, 108)			0.4		
ORGANIC IMPURITIES, FIG. NO. (CRD-C 121)	—	—	—	—	
SOFT PARTICLES, % (CRD-C 130)					—
% LIGHTER THAN SP. GR. ___ (CRD-C 122)					
% FLAT AND ELONGATED (CRD-C 119, 120)					
WT AV % LOSS, 5 CYC $MgSO_4$ (CRD-C 115)					
L.A. ABRASION LOSS, % (CRD-C 117, 145) GRADING A			29.1		
UNIT WT, LB/CU FT (CRD-C 106)			164.3		
FRIABLE PARTICLES, % (CRD-C 142)					
SPEC HEAT, BTU/LB/DEG F. (CRD-C 124)					
REACTIVITY WITH NaOH (CRD-C 128) SC, MM/L					
RC, MM/L					

MORTAR-MAKING PROPERTIES (CRD-C 116)

TYPE ___ CEMENT, RATIO ___ DAYS ___ , ___ DAYS ___

LINEAR THERMAL EXPANSION MILLIONTHS/DEG F. (CRD-C 125, 126):

ROCK TYPE	PARALLEL	ACROSS	ON	AVERAGE

MORTAR:

MORTAR-BAR EXPANSION AT 100F, % (CRD-C 123)	FINE AGGREGATE 3 MO.	6 MO.	9 MO.	12 MO.	COARSE AGGREGATE 3 MO.	6 MO.	9 MO.	12 MO.
LOW-ALK. CEMENT, % Na_2O EQUIVALENT:								
HIGH-ALK. CEMENT, % Na_2O EQUIVALENT:								

SOUNDNESS IN CONCRETE (CRD-C 40, 114)	FST	HW-CD	HD-CW
FINE AGG. COARSE AGG. DFE300			
FINE AGG. COARSE AGG. DFE300			

PETROGRAPHIC DATA (CRD-C 127):

The crushed stone from Granite Mountain Quarry is a speckled medium light gray, medium to coarse grained igneous rock classified as a syenite. Composition and textural characteristics are similar to those of granite. Physically, the stone is angular with rough surface texture. Twelve percent are considered flat as defined in CRD-C 119. Physically, the aggregate sample from this source appears structurally sound and durable and is free of potentially alkali-silica reactive constituents.

REMARKS:

ENG FORM 4011-R

APPENDIX II

MIXTURE PROPORTIONS

Mixture No.: A1

MATERIALS	S. S. D. WEIGHTS ONE CU YD BATCH (LB)	SOLID VOLUME ONE CU YD (CU FT)
Portland Cement	184.6	0.939
Fly Ash	98.8	0.626
Fine Agg.	1302.1	7.934
Coarse Agg. 3/4"	943.9	5.955
Coarse Agg. 1-1/2"	1151.5	6.991
AEA	3.1 oz	--
WRA	--	--
Water	200	3.205
Air		1.350
Total	3881.1	27.000

Mixture No.: A2

MATERIALS	S. S. D. WEIGHTS ONE CU YD BATCH (LB)	SOLID VOLUME ONE CU YD (CU FT)
Portland Cement	190.1	0.967
Fly Ash	101.7	0.644
Fine Agg.	1274.8	7.768
Coarse Agg. 3/4"	964.3	6.084
Coarse Agg. 1-1/2"	1176.6	7.142
AEA	3.2 oz	--
WRA	--	--
Water	190	3.045
Air		1.350
Total	3897.5	27.000

Mixture No.: A3		
MATERIALS	S. S. D. WEIGHTS ONE CU YD BATCH (LB)	SOLID VOLUME ONE CU YD (CU FT)
Portland Cement	195.3	0.994
Fly Ash	104.6	0.662
Fine Agg.	1282.7	7.816
Coarse Agg. 3/4"	970.4	6.122
Coarse Agg. 1-1/2"	1184.0	7.187
AEA	1.3 oz	--
WRA	18.0 oz	--
Water	178.3	2.869
Air		1.350
Total	3916	27.000

Mixture No.: A4		
MATERIALS	S. S. D. WEIGHTS ONE CU YD BATCH (LB)	SOLID VOLUME ONE CU YD (CU FT)
Portland Cement	208.2	1.059
Fly Ash	82.4	0.522
Fine Agg.	1299.1	7.916
Coarse Agg. 3/4"	941.7	5.941
Coarse Agg. 1-1/2"	1149.1	6.975
AEA	2.6 oz	--
WRA	--	--
Water	202	3.237
Air		1.350
Total	3882.5	27.000

Mixture No.: A5		
MATERIALS	S. S. D. WEIGHTS ONE CU YD BATCH (LB)	SOLID VOLUME ONE CU YD (CU FT)
Portland Cement	217.7	1.107
Fly Ash	86.1	0.546
Fine Agg.	1267.4	7.723
Coarse Agg. 3/4"	958.7	6.049
Coarse Agg. 1-1/2"	1169.7	7.100
AEA	3.0 oz	--
WRA	--	--
Water	195	3.125
Air		1.350
Total	3894.6	27.000

Volume of water is volume of water plus WRA

Mixture No.: A6		
MATERIALS	S. S. D. WEIGHTS ONE CU YD BATCH (LB)	SOLID VOLUME ONE CU YD (CU FT)
Portland Cement	218.1	1.110
Fly Ash	86.3	0.546
Fine Agg.	1282.7	7.816
Coarse Agg. 3/4"	970.4	6.122
Coarse Agg. 1-1/2"	1184.0	7.187
AEA	0.9 oz	--
WRA	18.3 oz	--
Water	178.3	2.869
Air		1.350
Total	3920.5	27.000

Mixture No.: A7		
MATERIALS	S. S. D. WEIGHTS ONE CU YD BATCH (LB)	SOLID VOLUME ONE CU YD (CU FT)
Portland Cement	236.6	1.204
Fly Ash	63.3	0.401
Fine Agg.	1328.7	8.096
Coarse Agg. 3/4"	923.3	5.825
Coarse Agg. 1-1/2"	1126.7	6.839
AEA	2.7 oz	--
WRA	--	--
Water	205	3.285
Air		1.350
Total	3883.6	27.000

Mixture No.: A8		
MATERIALS	S. S. D. WEIGHTS ONE CU YD BATCH (LB)	SOLID VOLUME ONE CU YD (CU FT)
Portland Cement	250.0	1.272
Fly Ash	66.9	0.424
Fine Agg.	1293.9	7.885
Coarse Agg. 3/4"	937.9	5.917
Coarse Agg. 1-1/2"	1144.4	6.947
AEA	3.5 oz	--
WRA	--	--
Water	200	3.205
Air		1.350
Total	3893.1	27.000

Volume of water is volume of water plus WRA

Mixture No.: A9		
MATERIALS	S. S. D. WEIGHTS ONE CU YD BATCH (LB)	SOLID VOLUME ONE CU YD (CU FT)
Portland Cement	253.7	1.291
Fly Ash	67.9	0.430
Fine Agg.	1306.4	7.960
Coarse Agg. 3/4"	947.0	5.974
Coarse Agg. 1-1/2"	1155.5	7.014
AEA	1.1 oz	--
WRA	19.3 oz	--
Water	185.3	2.981
Air		1.350
Total	3916.5	27.000

Volume of water is volume of water plus WRA

Mixture No.: A10		
MATERIALS	S. S. D. WEIGHTS ONE CU YD BATCH (LB)	SOLID VOLUME ONE CU YD (CU FT)
Portland Cement	212.5	1.081
Fly Ash	113.7	0.720
Fine Agg.	1241.4	7.564
Coarse Agg. 3/4"	980.5	6.186
Coarse Agg. 1-1/2"	1196.3	7.262
AEA	1.6 oz	--
WRA	19.6 oz	--
Water	176.3	2.837
Air		1.350
Total	3921.4	27.000

Mixture No.: A11		
MATERIALS	S. S. D. WEIGHTS ONE CU YD BATCH (LB)	SOLID VOLUME ONE CU YD (CU FT)
Portland Cement	232.0	1.180
Fly Ash	124.2	0.787
Fine Agg.	1200.2	7.313
Coarse Agg. 3/4"	990.3	6.248
Coarse Agg. 1-1/2"	1208.2	7.334
AEA	1.8 oz	--
WRA	--	--
Water	173.2	2.788
Air		1.350
Total	3928.9	27.000

Volume of water is volume of water plus WRA

Mixture No.: A12		
MATERIALS	S. S. D. WEIGHTS ONE CU YD BATCH (LB)	SOLID VOLUME ONE CU YD (CU FT)
Portland Cement	158.2	0.805
Fly Ash	127.1	0.805
Fine Agg.	1325.3	8.076
Coarse Agg. 3/4"	960.7	6.061
Coarse Agg. 1-1/2"	1172.1	7.115
AEA	1.4 oz	--
WRA	17.1 oz	--
Water	173.4	2.788
Air		1.350
Total	3916.8	27.000

Volume of water is volume of water plus WRA

Mixture No.: A13		
MATERIALS	S. S. D. WEIGHTS ONE CU YD BATCH (LB)	SOLID VOLUME ONE CU YD (CU FT)
Portland Cement	171.0	0.870
Fly Ash	137.4	0.870
Fine Agg.	1285.5	7.833
Coarse Agg. 3/4"	972.4	6.135
Coarse Agg. 1-1/2"	1186.5	7.202
AEA	1.5 oz	--
WRA	18.5 oz	--
Water	170.3	2.740
Air		1.350
Total	3923.1	27.000

Volume of water is volume of water plus WRA

Mixture No.: A14		
MATERIALS	S. S. D. WEIGHTS ONE CU YD BATCH (LB)	SOLID VOLUME ONE CU YD (CU FT)
Portland Cement	180.0	0.916
Fly Ash	144.6	0.916
Fine Agg.	1253.8	7.640
Coarse Agg. 3/4"	990.3	6.248
Coarse Agg. 1-1/2"	1208.2	7.334
AEA	1.9 oz	--
WRA	19.5 oz	--
Water	161.3	2.596
Air		1.350
Total	3938.2	27.000

Volume of water is volume of water plus WRA

Mixture No.: A15		
MATERIALS	S. S. D. WEIGHTS ONE CU YD BATCH (LB)	SOLID VOLUME ONE CU YD (CU FT)
Portland Cement	137.9	0.701
Fly Ash	165.0	1.051
Fine Agg.	1300.3	7.923
Coarse Agg. 3/4"	983.6	6.206
Coarse Agg. 1-1/2"	1200.1	7.285
AEA	2.1 oz	--
WRA	18.2 oz	--
Water	154.3	2.484
Air		1.350
Total	3941.2	27.000